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VELOCITY REQUIREMENTS FOR THE EARTH RETURN  
PHASE OF PLANETARY MISSIONS

By Robert M. Jones and William T. Stephens  
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ABSTRACT

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Retro characteristic velocity requirements have been calculated for the earth return phase of planetary missions with maximum allowable earth entry velocities. The effects of key independent performance parameters on the characteristic velocity and associated burning time requirements have been investigated for the retro maneuver. The propulsion systems considered were low-energy chemical, high-energy chemical, and solid-core nuclear.

Results are presented graphically in parametric form, showing characteristic velocity and burning time as a function of approach hyperbolic excess velocity, maximum allowable entry velocity, thrust-to-weight ratio, specific impulse and entry flight path angle. The allowable earth entry velocity ranges from local parabolic to 18 km/sec.

Author

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PROPULSION AND VEHICLE ENGINEERING LABORATORY  
RESEARCH AND DEVELOPMENT OPERATIONS

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# LIST OF SYMBOLS

<u>Symbol</u>	<u>Definition</u>
$F$	Thrust
$F/W_o$	Thrust-to-weight ratio
$g$	Acceleration of gravity for a mean spherical, rotating Earth = $9.80655 \text{ m/sec}^2$
$g_n$	Mean apparent gravity at sea level; international standard for weight-mass conversion; $9.81992 \text{ m/sec}^2$
$I_{sp}$	Specific Impulse
$m$	Mass
$r$	Radius from center of the Earth to vehicle
$r_o$	Radius to vehicle at initial conditions
$r_E$	Radius to vehicle at reentry conditions
$r_\oplus$	Radius of mean spherical Earth
$t_b$	Burning time of engine
$V$	Inertial velocity
$V_e$	Reentry velocity
$\Delta V_c$	Characteristic velocity
$\Delta(\Delta V_c)$	Change in characteristic velocity
$V_\infty$	Hyperbolic excess velocity
$V_\infty(\text{EMOS})$	Hyperbolic excess velocity normalized to Earth's mean orbital speed ( $\frac{V_\infty}{\text{EMOS}}$ )

# LIST OF SYMBOLS - Continued

<u>Symbol</u>	<u>Definition</u>
$W_o$	Initial weight prior to reentry
$W_p$	Propellant weight
$x$	Range
$\beta$	Thrust vector orientation angle measured from the velocity vector to the thrust vector (positive clockwise)
$\theta$	Flight path angle, measured from the local vertical (positive clockwise)
$\theta_E$	Reentry angle, measured from the local vertical to the velocity vector (positive clockwise, $\theta_E = \theta - 180^\circ$ )
$\psi$	Central angle measured from local radius vector at ignition
$\zeta$	Propellant ratio, $\frac{W_p}{W_o}$
$\mu_\oplus$	Gravitational constant of the Earth

<u>Subscripts</u>	<u>Definition</u>
$o$	Initial
$\oplus$	Earth
$e$	Reentry
$ref$	Reference conditions
$r$	The arbitrary altitude for which velocity, thrust-to-weight ratio, etc., are calculated

LIST OF SYMBOLS - Concluded

<u>Abbreviations</u>	<u>Definition</u>
deg	Degrees
km	Kilometers
m	Meters
lb	Pounds
s or sec	Seconds



# VELOCITY REQUIREMENTS FOR THE EARTH RETURN PHASE OF PLANETARY MISSIONS

By Robert M. Jones and William T. Stephens

George C. Marshall Space Flight Center

## SUMMARY

Retro characteristic velocity requirements have been calculated for the earth return phase of planetary missions with maximum allowable earth entry velocities. The effects of key independent performance parameters on the characteristic velocity and associated burning time requirements have been investigated for the retro maneuver. The propulsion systems considered were low-energy chemical, high-energy chemical, and solid-core nuclear.

Results are presented graphically in parametric form, showing characteristic velocity and burning time as a function of approach hyperbolic excess velocity, maximum allowable entry velocity, thrust-to-weight ratio, specific impulse and entry flight path angle. The allowable earth entry velocity ranges from local parabolic to 18 km/sec.

## SECTION I. INTRODUCTION

Preliminary mission analysis and vehicle design usually require a comprehensive knowledge of key performance parameters, particularly the mission characteristic velocity requirements. Furthermore, in view of the iterative processes of preliminary design and feasibility studies, it is desirable to have performance data in a parametric format with a wide variation of the key independent performance parameters.

Parametric data of this type have been presented for various phases of planetary missions in References 1 through 4. References 2, 3 and 4 present data for the earth departure, planet arrival and planet departure phases of typical Mars and Venus stopover missions.

However, data for the final phase of such missions, the earth return maneuver, are not included in these references.

Extensive studies have been made of the atmospheric flight portion of the earth return trajectory for planetary-class missions. Little data are available, however, for the retro-brake maneuver which may be required prior to atmospheric entry. This is the case when there is a limited entry speed the entry body can tolerate due to heat, g-loading or guidance restrictions. For example, unbraked earth reentry speeds of 16 km/sec (65,617 ft/sec) are not uncommon for Mars stopover missions. On the other hand, current estimates for allowable entry speeds, based on advanced technology, range from parabolic velocity (about 11 km/sec) to as high as 22 km/sec, an uncertainty factor of two. Until a higher degree of confidence is achieved for the high entry speeds, the mission planner must consider the possibility of having a retro during the earth return phase.

It is the purpose of this report to present parametric data illustrating the variation of characteristic velocity and the associated burning times for propulsive braking to various earth entry speeds from a wide range of approach hyperbolic excess velocities. Data are presented for a range of specific impulse values which typify storable chemical, high-energy chemical and solid-core nuclear propulsion systems. Single-stage braking is assumed in all cases. All calculations were made on an IBM 7090 computer using a Runge-Kutta numerical integration technique.

## SECTION II. ASSUMPTIONS

The principal assumptions related to the analysis discussed and the results presented in this report are as follows:

- (1) Deceleration via a single stage from an interplanetary transfer trajectory to specified end conditions.
- (2) Tangential thrust
- (3) Burnout altitude - 185 km

(4) Range of independent performance parameters:

$$V_{\infty} = 0.1 - 0.6 \text{ EMOS}$$

$$F/W_o = 0.05 - 1.0$$

$$\text{Storable propellant } I_{sp} = 320 - 340 \text{ sec}$$

$$\text{High-energy chemical } I_{sp} = 420 - 440 \text{ sec}$$

$$\text{Solid-core nuclear } I_{sp} = 775 - 825 \text{ sec}$$

$$\theta_E = 60^\circ - 90^\circ$$

$$(V_e)_{\max} = 11.03 - 18.0 \text{ km/sec}$$

(5) Mean spherical earth model with

$$\mu_{\oplus} = 398,613 \text{ km}^3/\text{sec}^2$$

$$r_{\oplus} = 6371.1 \text{ km}$$

(6) Earth mean orbital speed (EMOS) = 29,770 m/sec

### SECTION III. ANALYSIS

The method employed in this analysis is based on the terminology and general equations of motion outlined in Reference 1. Referring to the following sketch, the general equations of motion for a point mass moving in planar motion under the influence of a central gravitational potential are as follows:

$$\dot{V} = \frac{F \cos \beta}{m} - g \cos \theta \quad (1)$$

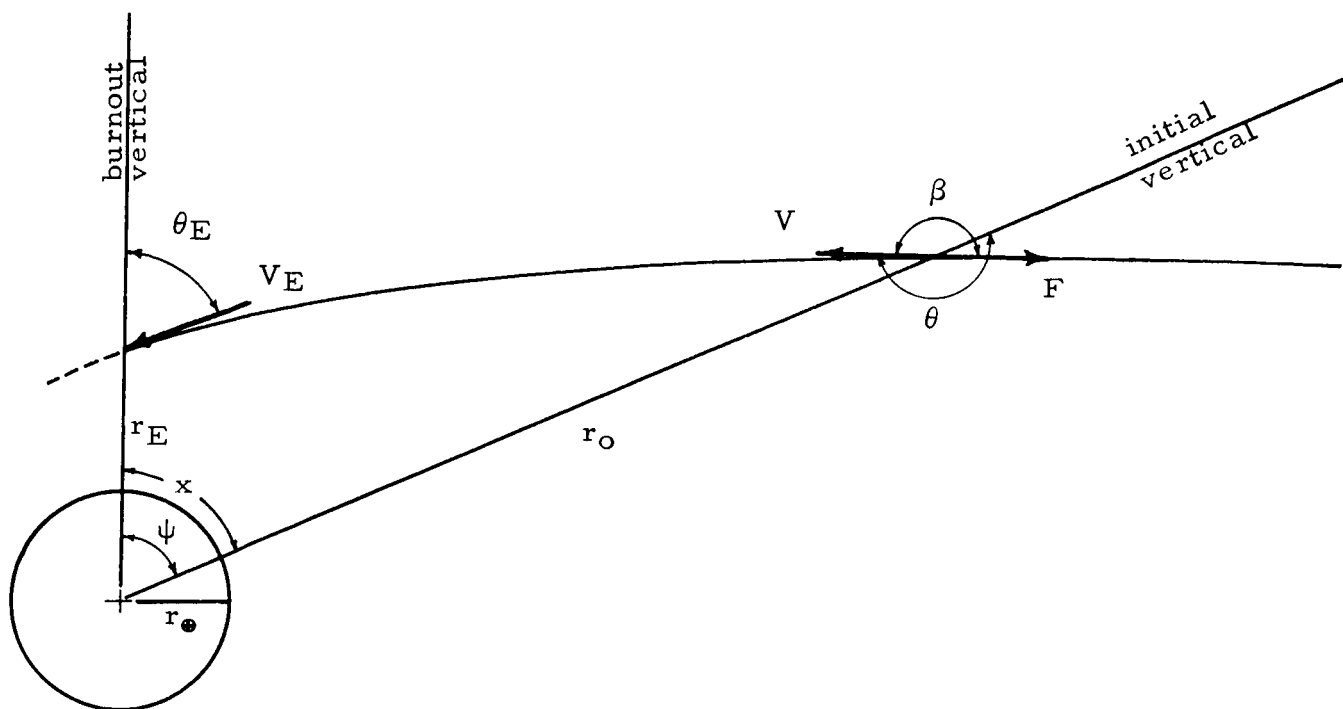
$$\dot{\theta} = \frac{F \sin \beta}{mV} + \left( \frac{g}{V} - \frac{V}{r} \right) \sin \theta \quad (2)$$

where

$$m = m_o + \int \dot{m} dt$$

and

$$\dot{m} = -F/V_{ex}$$



For tangential thrust braking,  $\beta = 180^\circ$ , the above equations reduce to

$$\dot{V} = -\frac{F}{m} - g \cos \theta \quad (3)$$

$$\dot{\theta} = \left(\frac{g}{V} - \frac{V}{r}\right) \sin \theta \quad (4)$$

Numerical integration of equations 3 and 4 determines the velocity and flight path angle. Thus,

$$V = \int \dot{V} dt \quad (5)$$

$$\theta = \int \dot{\theta} dt \quad (6)$$

Range and altitude are then calculated by the relations

$$X = \int \frac{r_\oplus}{r} V \sin \theta dt \quad (7)$$

$$r = r_\oplus + \int V \cos \theta dt \quad (8)$$

With burning time having been determined during the numerical integration of the equations of motion, the propellant ratio for constant thrust and specific impulse can be calculated from the relationship

$$\zeta = \left( \frac{F}{W_o} \right) \frac{t_b}{I_{sp}} \quad (9)$$

Once  $\zeta$  is determined the main parameter of interest in the present study, the stage characteristic velocity, can be found from

$$\Delta V_c = g_n I_{sp} \ln \frac{1}{1-\zeta} \quad (10)$$

where characteristic velocity represents the energy actually expended by the stage in braking from the approach velocity to the desired entry velocity, taking into account "gravity losses" which, in the case of braking, represent the undesirable acceleration caused by the gravitational attraction.

The velocity at initiation of braking ( $t = 0$ ) is given by the equation

$$V_o = \sqrt{(V_\infty)^2 + (V_{esc})^2} \quad r = r_o \quad (11)$$

where  $V_{esc}$  is the local parabolic escape velocity and  $V_\infty$  is the hyperbolic excess velocity associated with the approach trajectory.

Burnout or reentry conditions, for the case of a braking maneuver, are preset, and the initial conditions, which result in the desired end values, must be determined for each combination of the independent performance parameters. Thus, the calculation of the braking trajectory and velocity requirements is a "reverse integration" problem. Initially, the reentry altitude,  $r_E$ , and the flight path angle,  $\theta_E$ , were fixed and the entry velocity,  $V_e$ , varied from local parabolic up to 18 km/sec. Then, with  $r_E$  remaining fixed,  $\theta_E$  was allowed to vary from  $60^\circ - 90^\circ$  over the full range of  $V_e$ .

#### SECTION IV. DISCUSSION OF RESULTS

Before proceeding into the discussion of results, it is of interest to note the variation of entry velocity at the assumed burnout altitude of 185 km if no propulsive braking is employed. This variation is shown as a function of  $V_\infty$  in Figure 1 with  $V_e$  being calculated from

$$V_e = \sqrt{(V_\infty)^2 + (V_{esc})^2} \quad r = r_E$$

which is similar to equation 11 but with  $V_{esc}$  being calculated at 185 km. This curve is shown for reference and to illustrate that, depending upon the approach  $V_\infty$  and the allowable  $V_e$ , there may or may not be a retro maneuver required. This explains why, in some later figures, the characteristic velocity requirements go to zero at a relatively high value of  $V_\infty$ . For example, Figure 1 indicates that if the allowable entry speed at 185 km were 20 km/sec there would be no retro required for values of  $V_\infty$  below 0.56 EMOS ( $V_\infty$  is commonly expressed as a fraction of the earth's mean orbital speed, EMOS, but must be in km/sec for equation 11). Previous studies indicate that the  $V_\infty$  at earth return from realistic Mars and Venus flyby and stopover missions does not often exceed 0.5 EMOS, or an unbraked entry velocity of just over 18 km/sec. Consequently, a  $V_e$  of 18 km/sec was the maximum considered.

Figures 2a through 2d show parametrically the characteristic velocity requirements for retro to allowable entry velocities at 185 km of 11.03 (local parabolic escape), 12, 14, 16, and 18 km/sec for a specific impulse of 320 seconds. Similar data are shown in Figures 3a through 3d and in Figures 4a through 4d for specific impulses of 330 and 340 seconds, respectively, completing the assumed range of specific impulse for storable propellant retro systems. Analogous data for the high-energy chemical systems is presented in Figures 5 through 7, followed by data for nuclear systems in Figures 8 through 10.

All of the data presented in Figures 2 through 10 are for the nominal flight path angle of  $90^\circ$ . Figures 11 through 22 illustrate

the increase in characteristic velocity for non-reference flight path angles. The characteristic velocity for a non-reference entry flight path angle is found by adding the associated penalty to the  $\Delta V_c$  for  $\theta = 90^\circ$ , i.e.,

$$(\Delta V_c)_\theta = (\Delta V_c)_{\theta = 90^\circ} + \Delta (\Delta V_c)_\theta \quad (12)$$

Burning time requirements for the various combinations of  $I_{sp}$  and  $(V_e)_{max}$  are shown parametrically in Figures 23 through 25 for the reference entry conditions. Burning times for non-reference flight path angles can be calculated from the relationship

$$(t_b)_\theta = (t_b)_{\theta = 90^\circ} + \Delta t_b \quad (13)$$

where  $(t_b)_{\theta = 90^\circ}$  is read directly from the graphs and  $\Delta t_b$  is calculated from

$$\Delta t_b = \frac{I_{sp}}{F/W_o} \left[ 1 - e^{\frac{-\Delta(\Delta V_c)}{g_n I_{sp}}} \right] \quad (14)$$

In the above equation,  $\Delta(\Delta V_c)$  is also read directly from the appropriate graph for the particular non-reference value of  $\theta$ .

## SECTION V. CONCLUSIONS

Use of the parametric data presented in this report provides the mission planner with sufficient information to make quick preliminary estimates of the stage design required for the earth return phase of various mission profiles. The data are comprehensive enough to allow quick sensitivity studies to determine the effect of such key performance parameters as maximum allowable entry velocity and entry flight path angle upon the preliminary design of the retro stage.

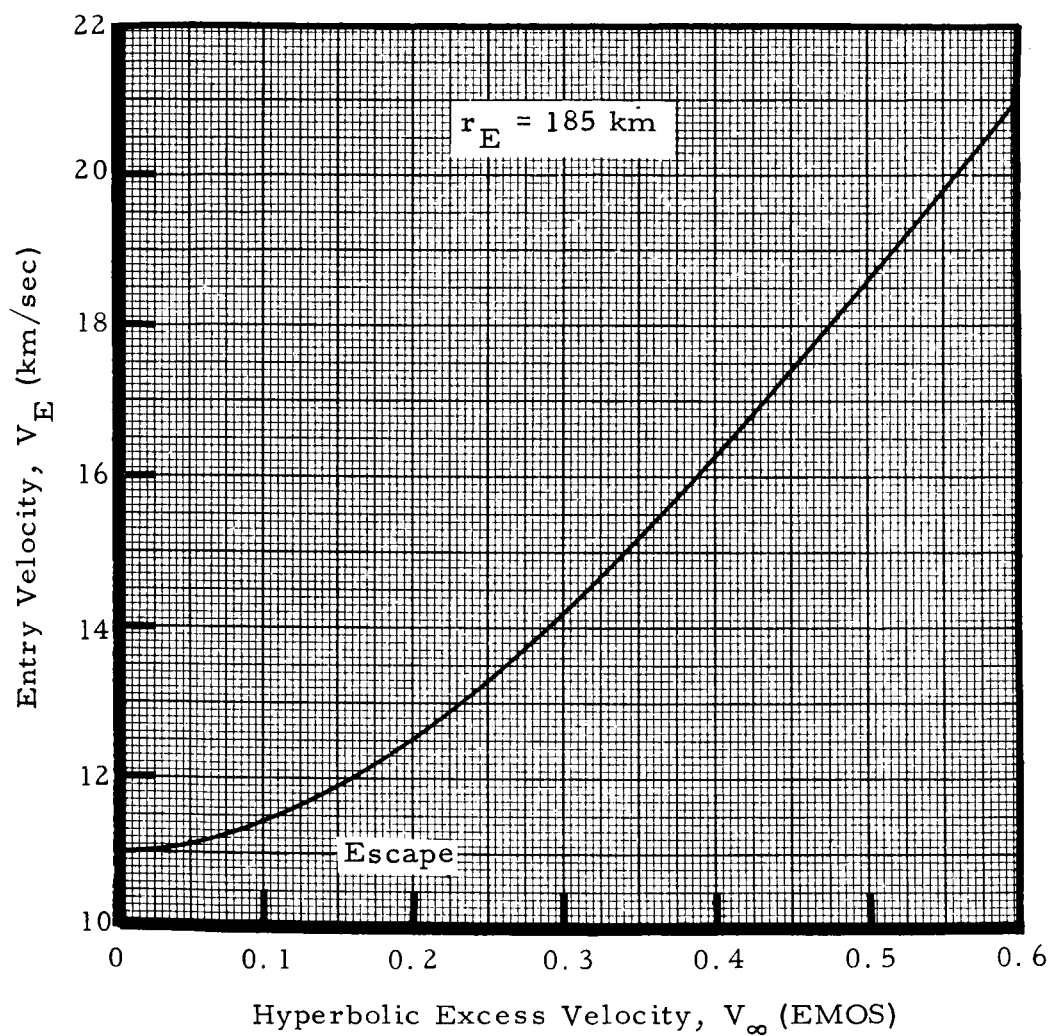


FIGURE 1. VARIATION OF ENTRY VELOCITY WITH HYPERBOLIC EXCESS VELOCITY



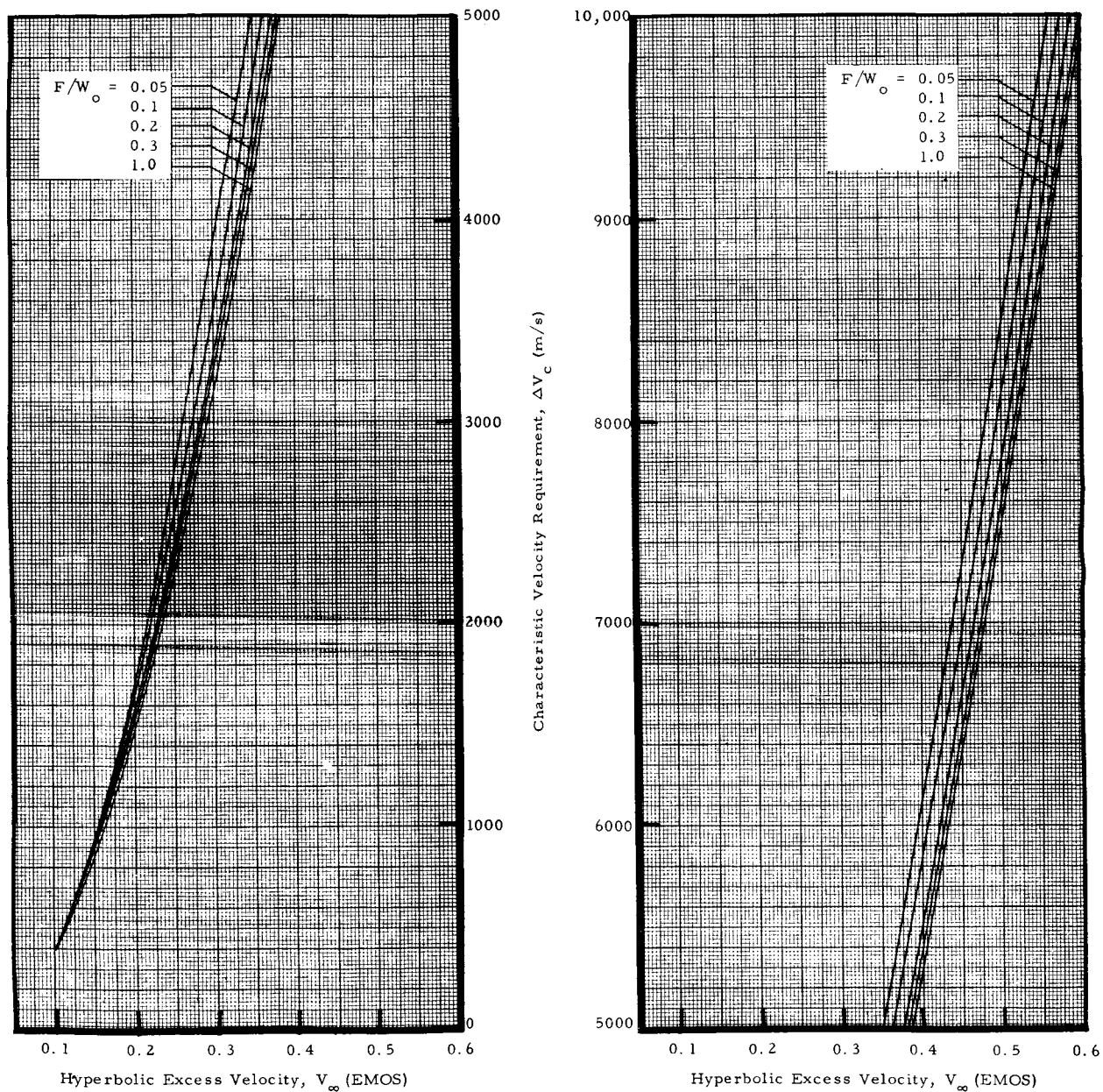


FIGURE 2a. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 320$  s  
 $(V_e)_{max} = 11030$  m/s

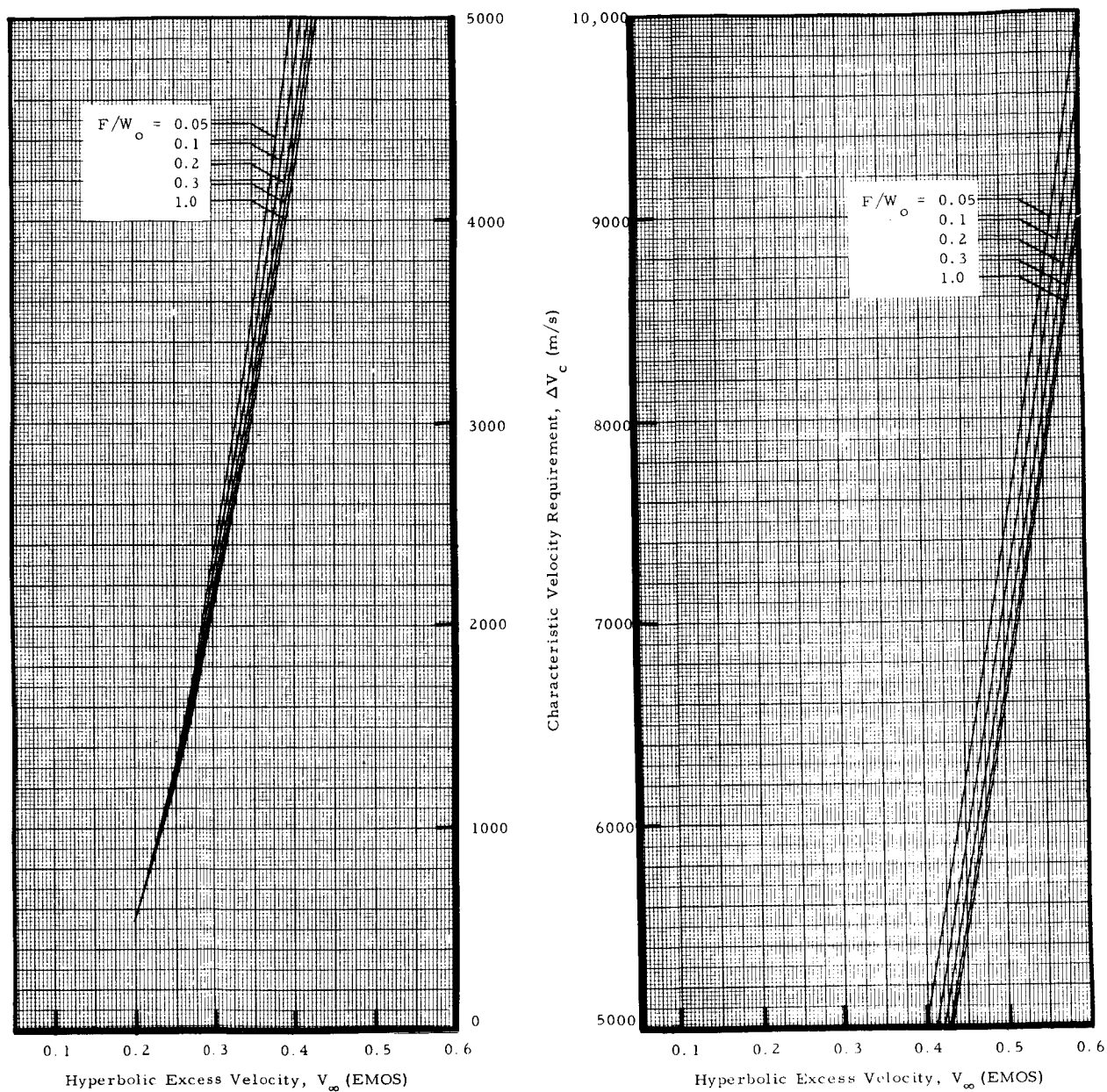


FIGURE 2b. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 320$  s  
 $(V_e)_{max} = 12000$  m/s

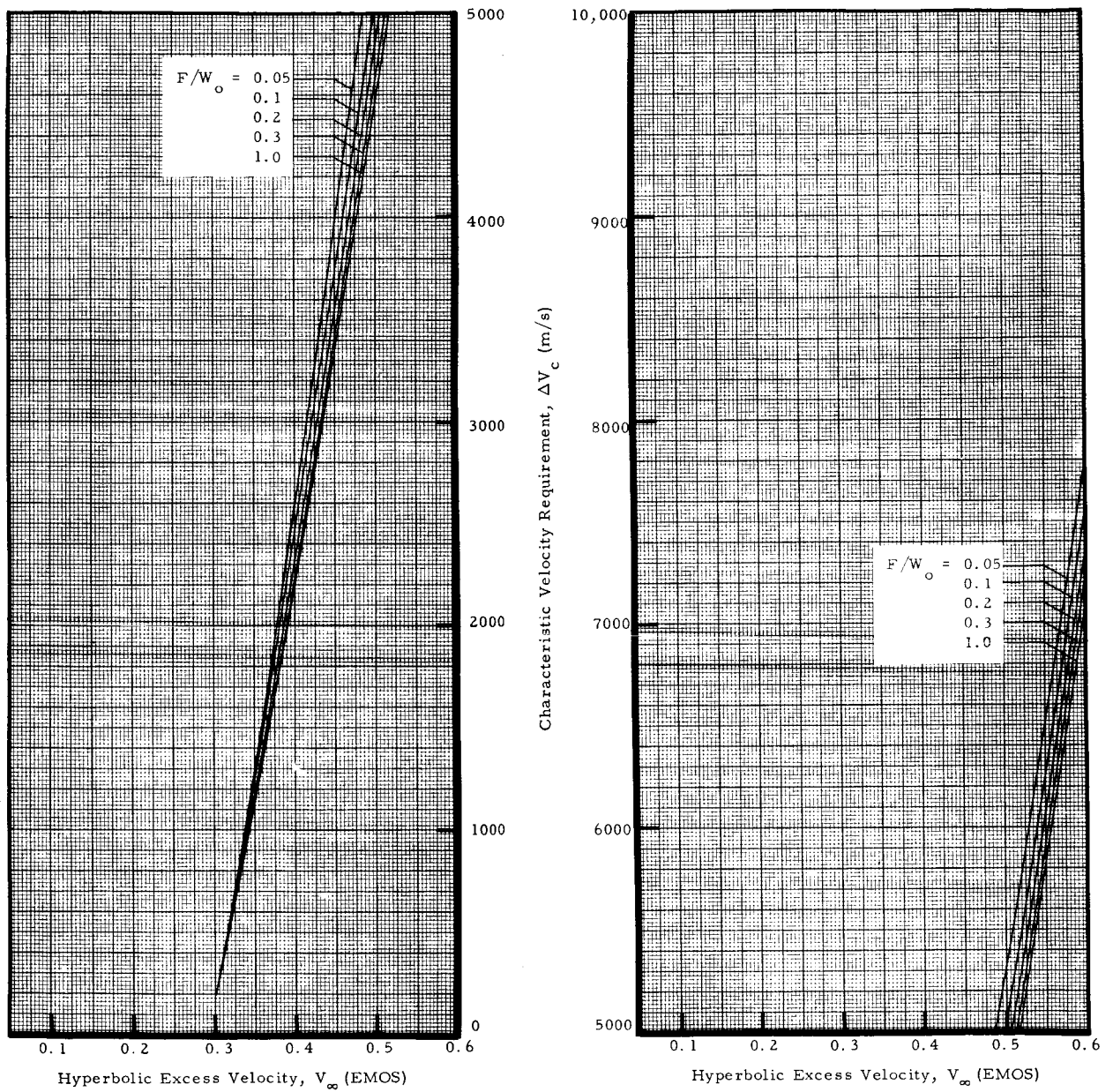
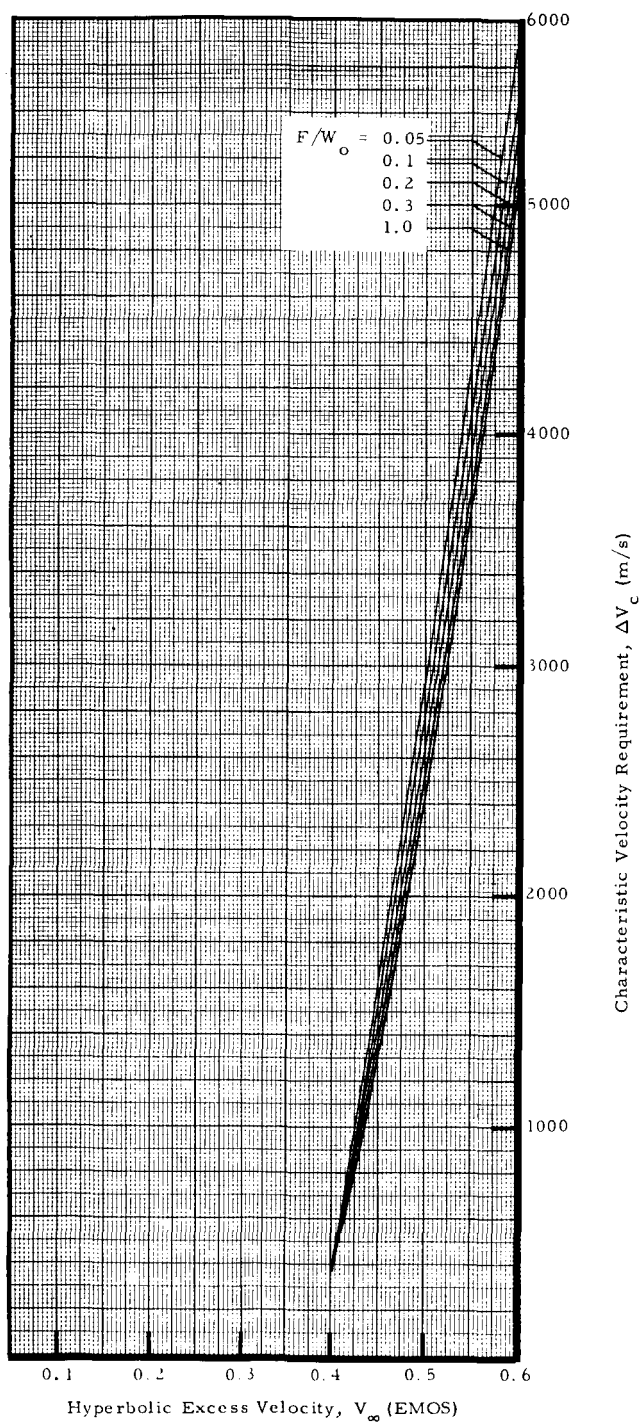
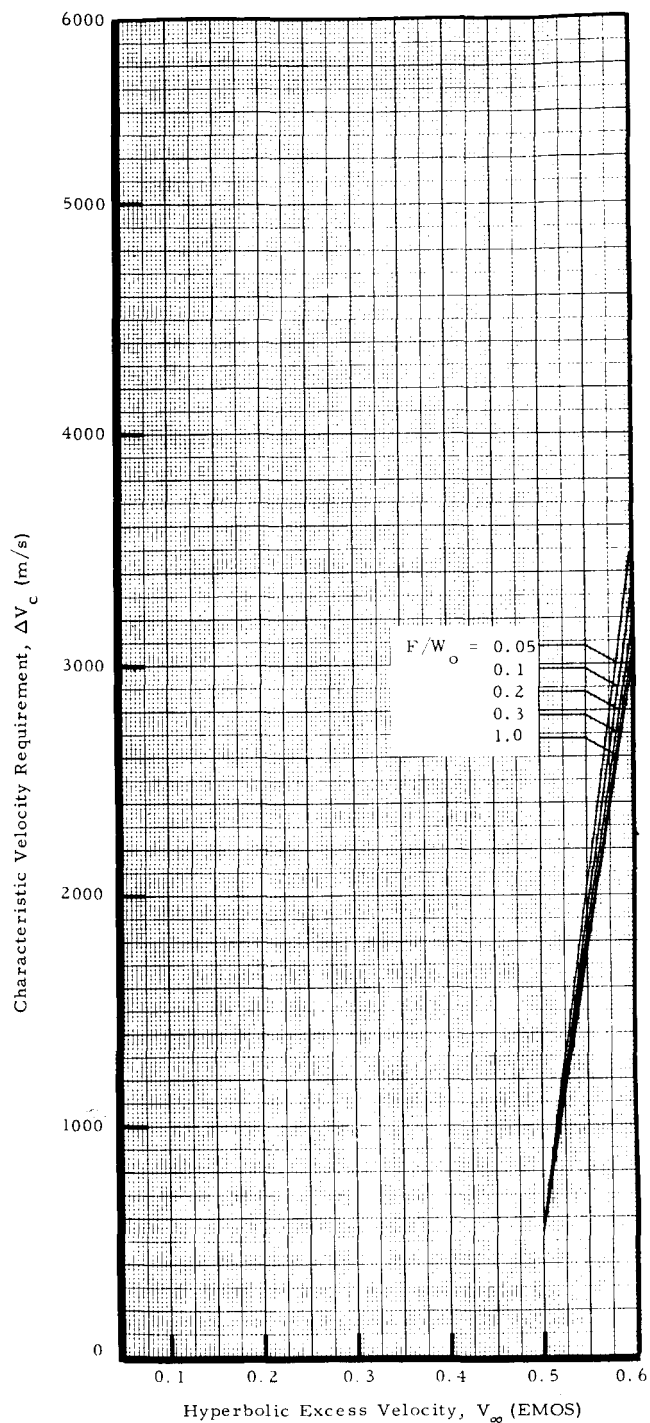


FIGURE 2c. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $t_{sp} = 320$  s  
 $(V_e)_{max} = 14000$  m/s



a.  $(V_e)_{\max} = 16000$  m/s



b.  $(V_e)_{\max} = 18000$  m/s

FIGURE 2d. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 320$  s

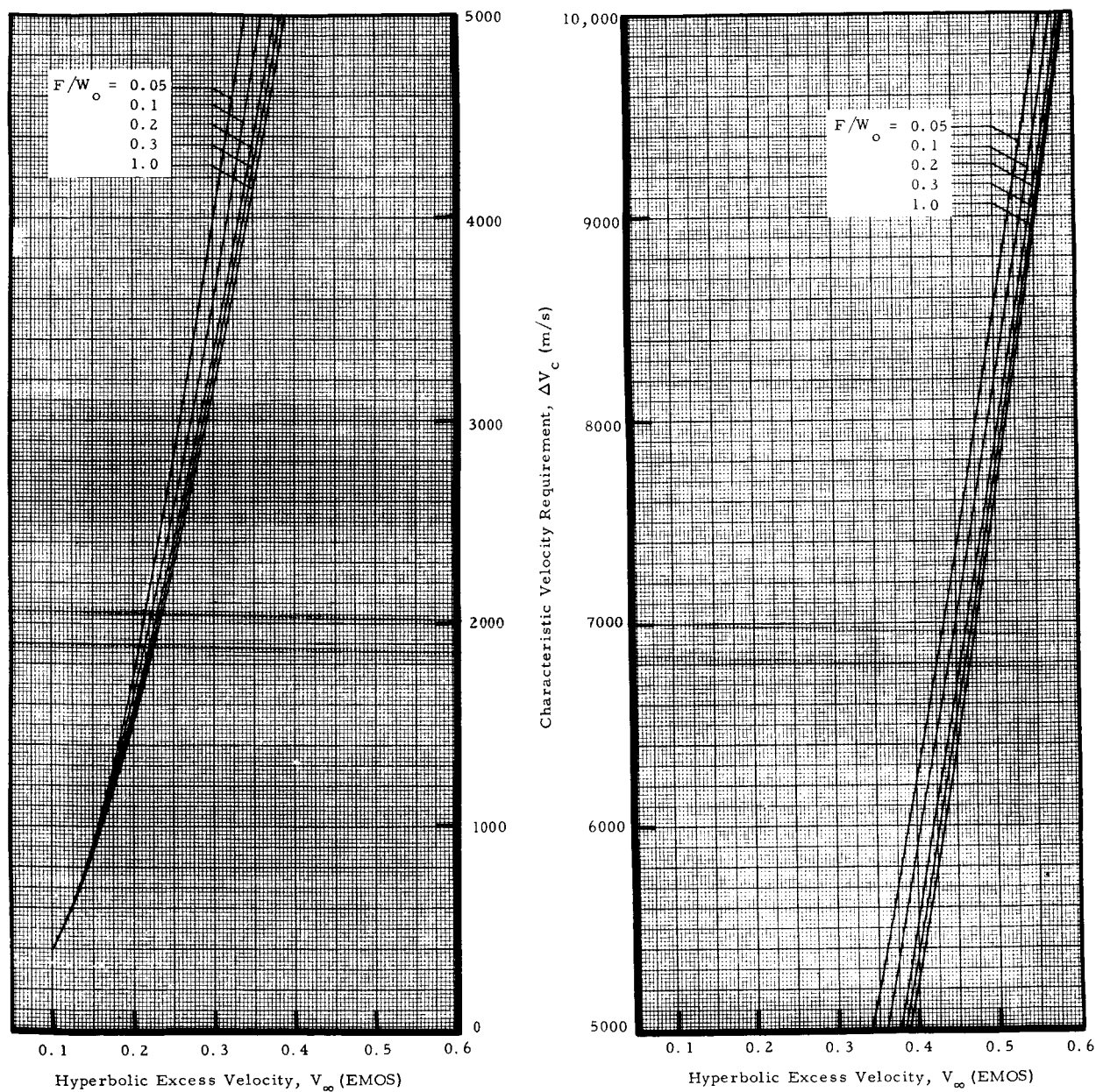


FIGURE 3a. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 330$  s  
 $(V_e)_{max} = 11030$  m/s



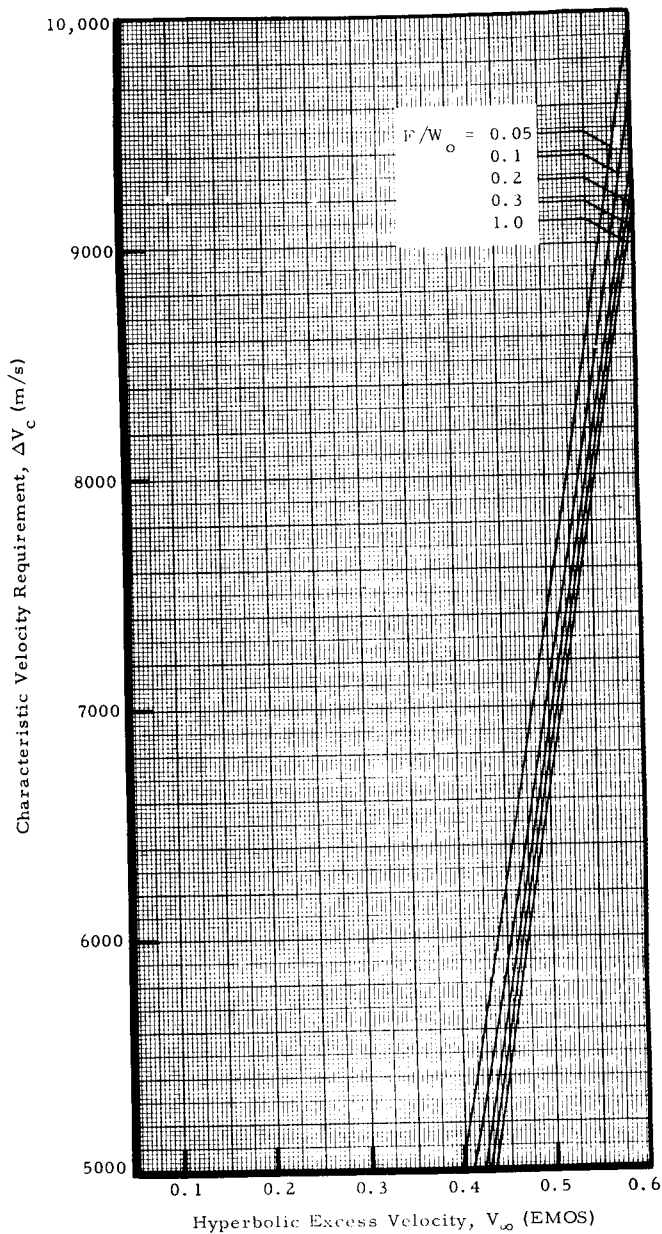
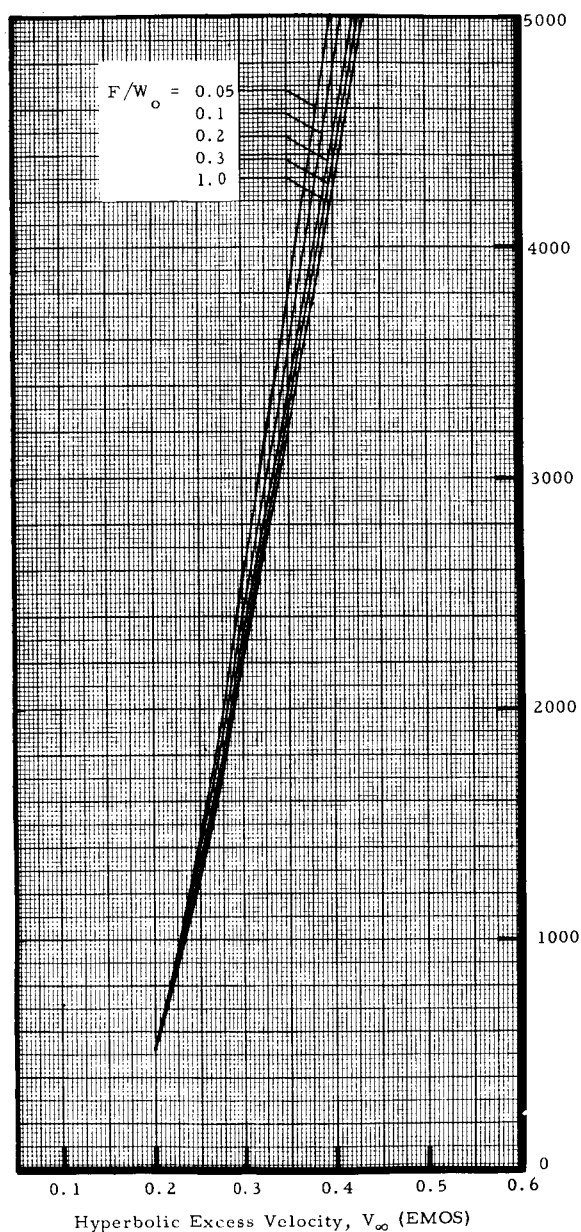


FIGURE 3b. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $t_{sp} = 330$  s  
 $(V_e)_{\max} = 12000$  m/s

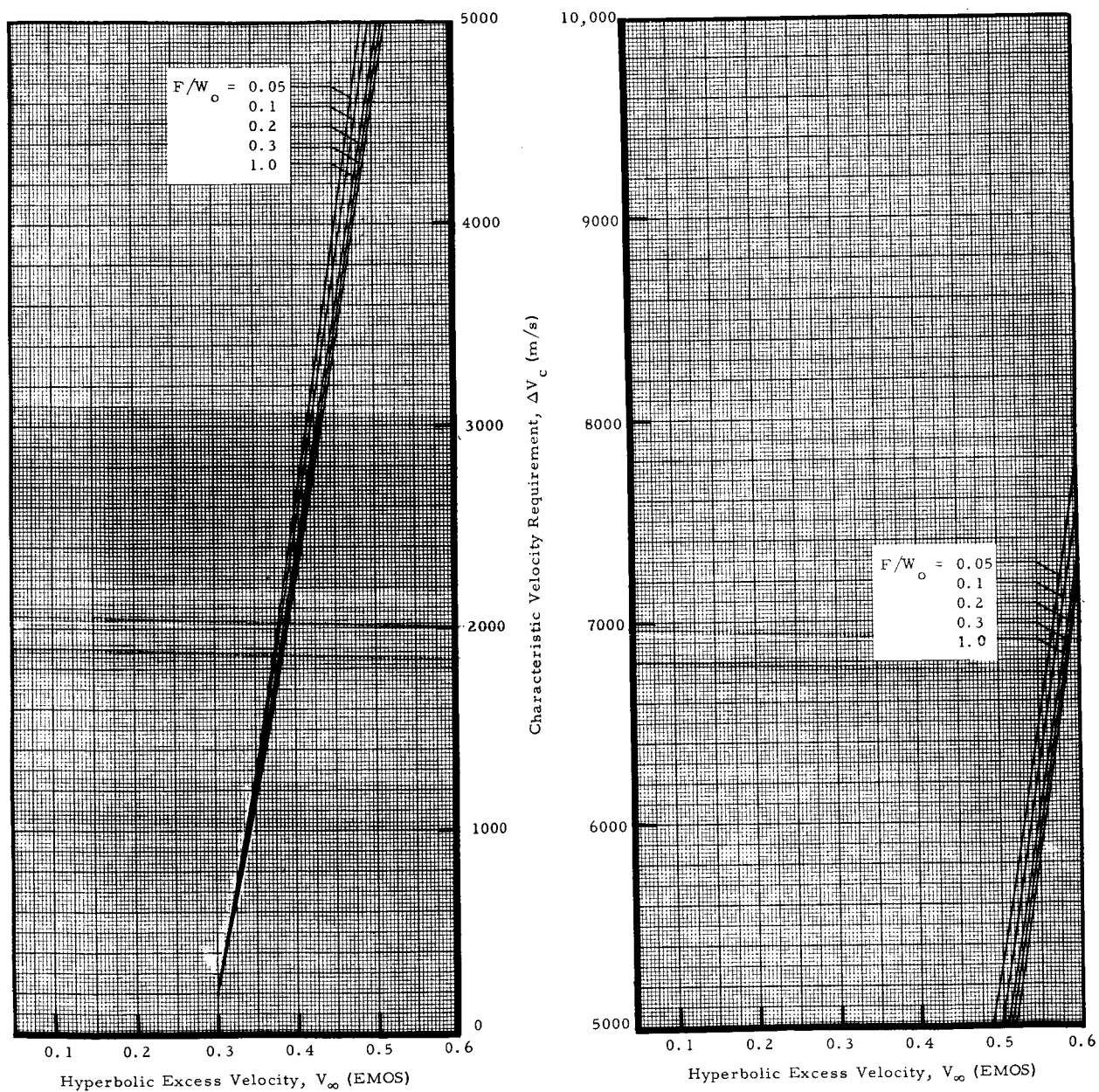
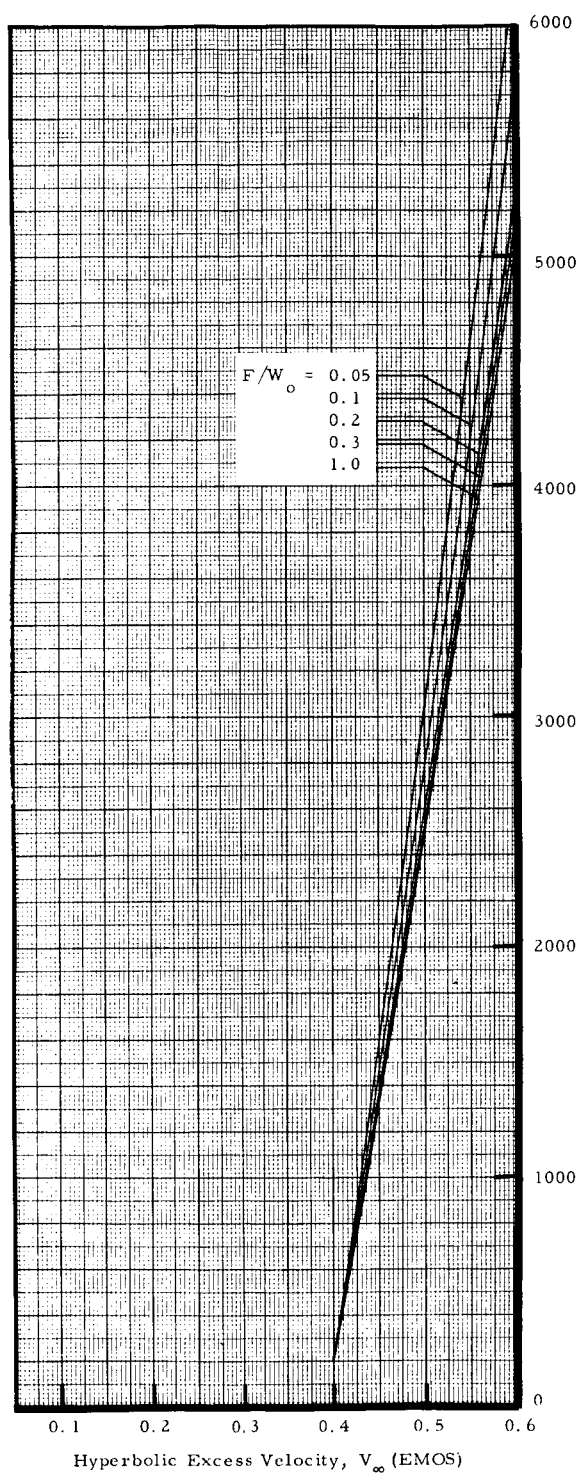
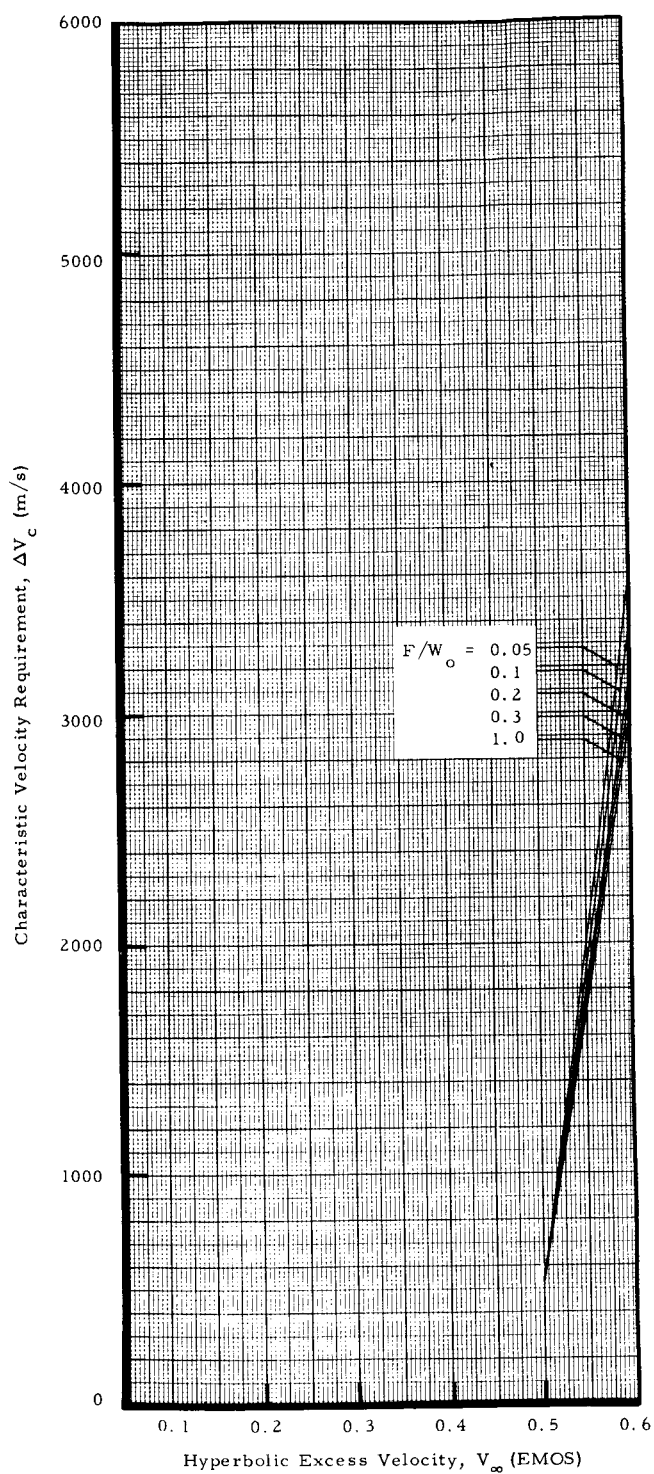


FIGURE 3c. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 330$  s  
 $(V_e)_{max} = 14000$  m/s



a.  $(V_e)_{\max} = 16000$  m/s



b.  $(V_e)_{\max} = 18000$  m/s

FIGURE 3d. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 330$  s



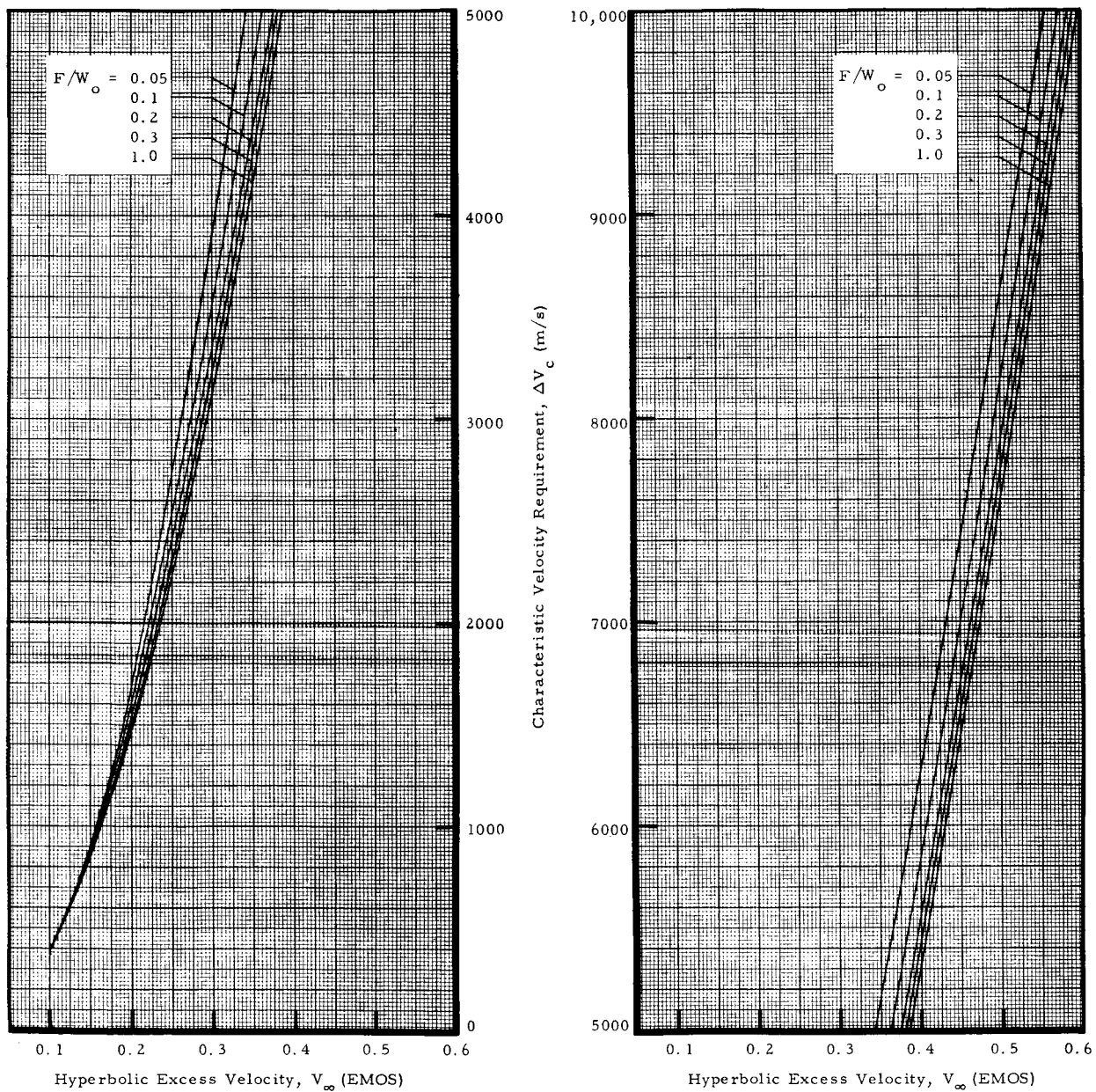


FIGURE 4a. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $i_{sp} = 340$  s  
 $(V_e)_{max} = 11030$  m/s

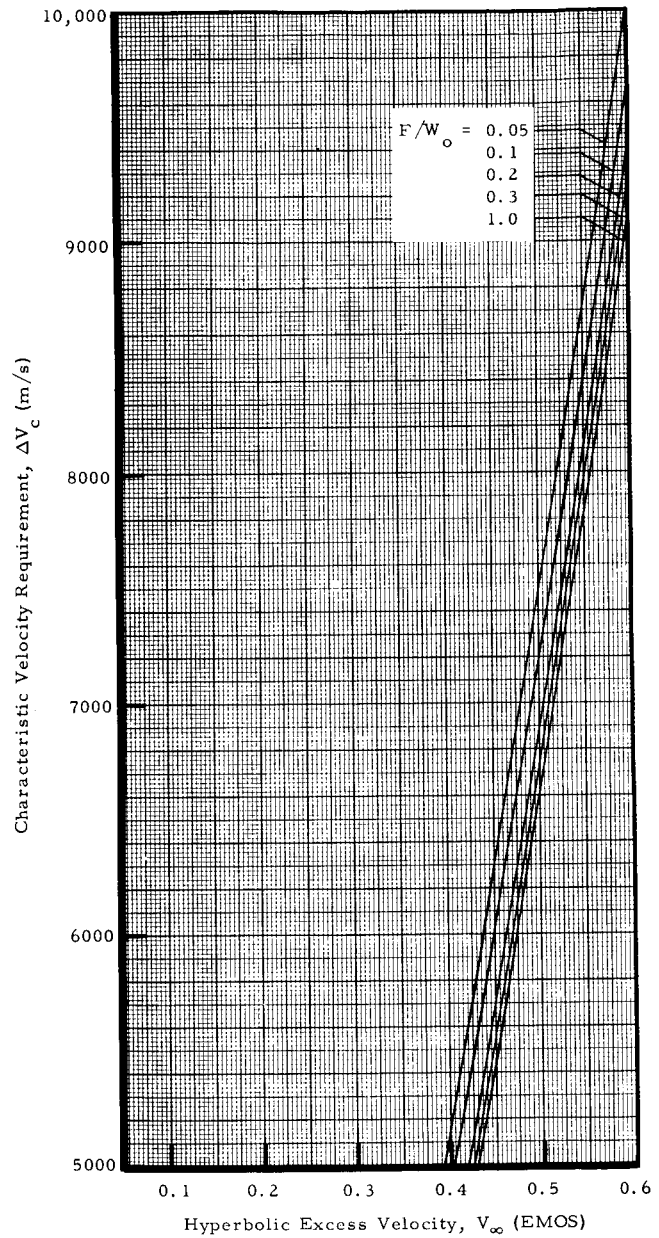
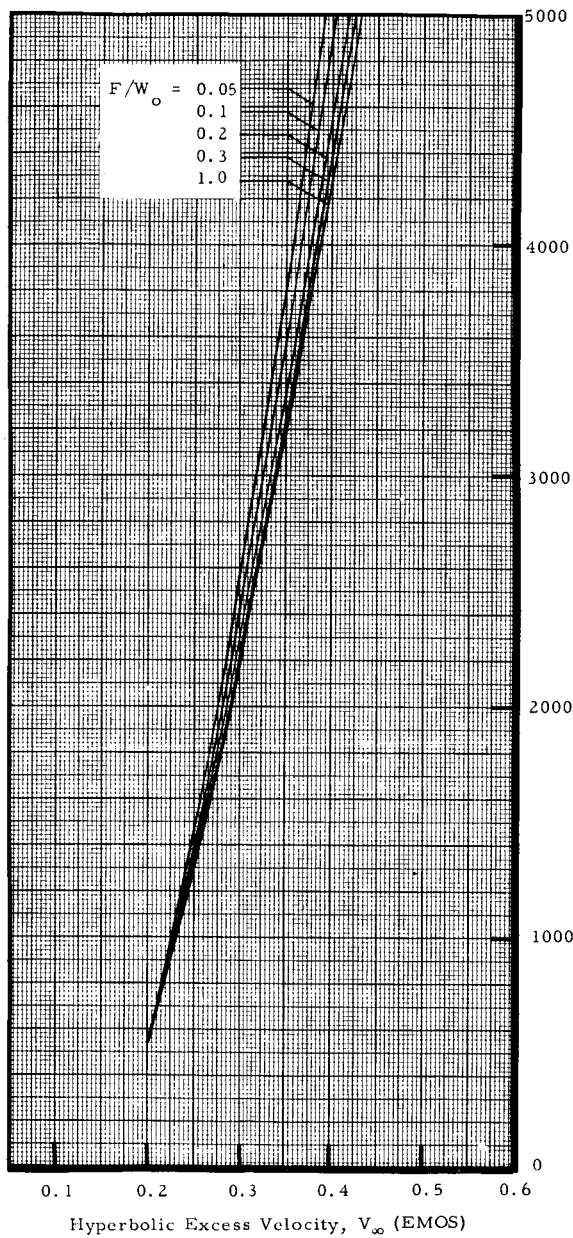


FIGURE 4b. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 340$  s  
 $(V_e)_{max} = 12000$  m/s

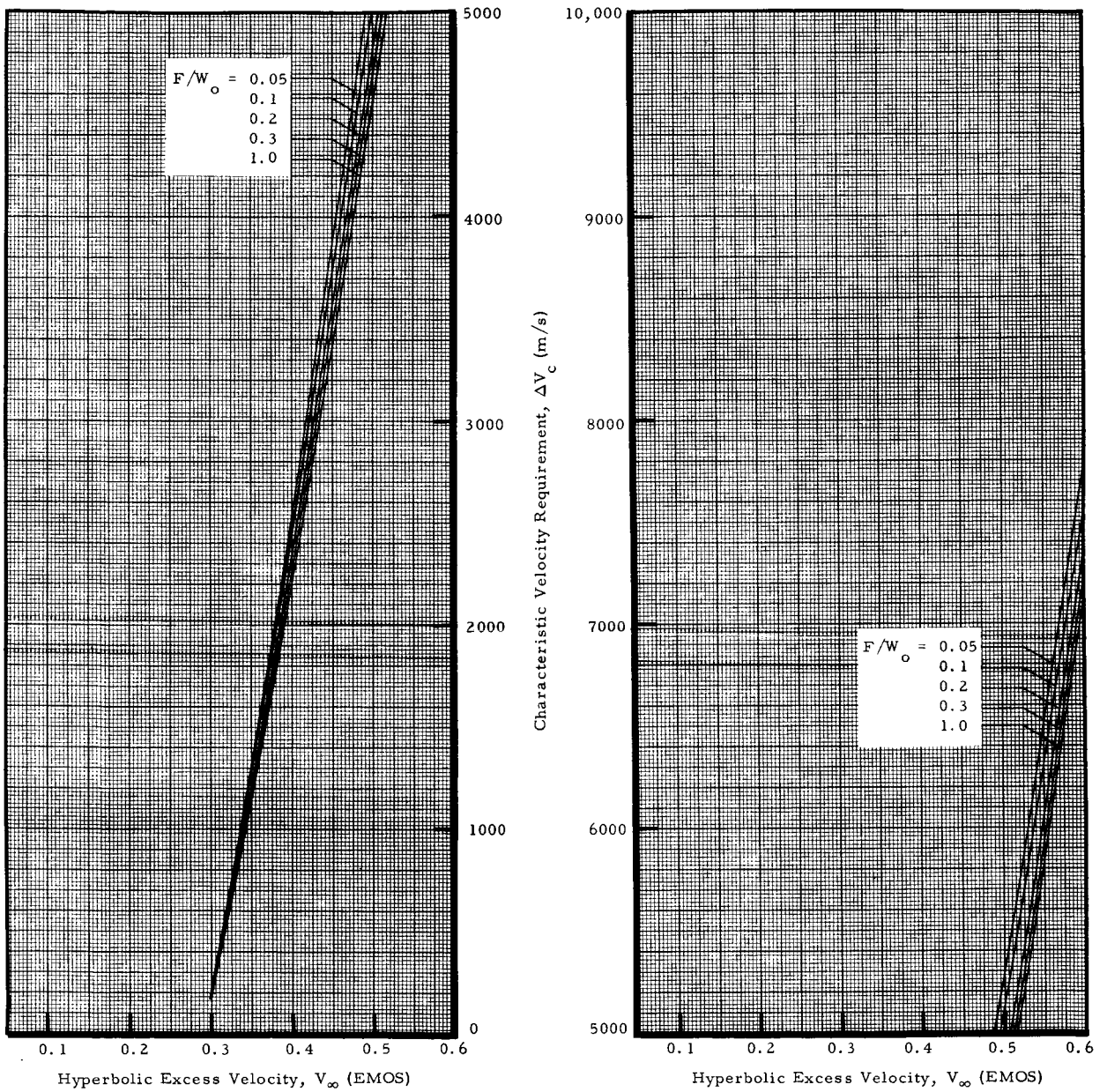
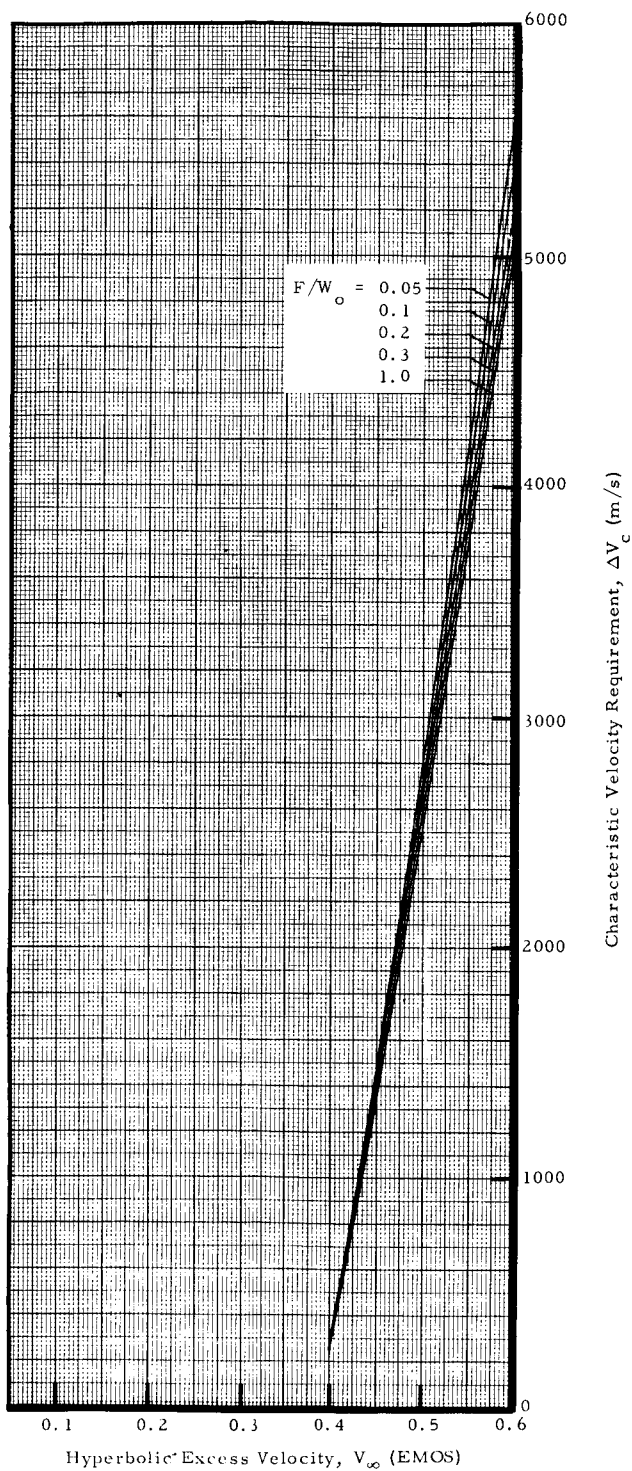
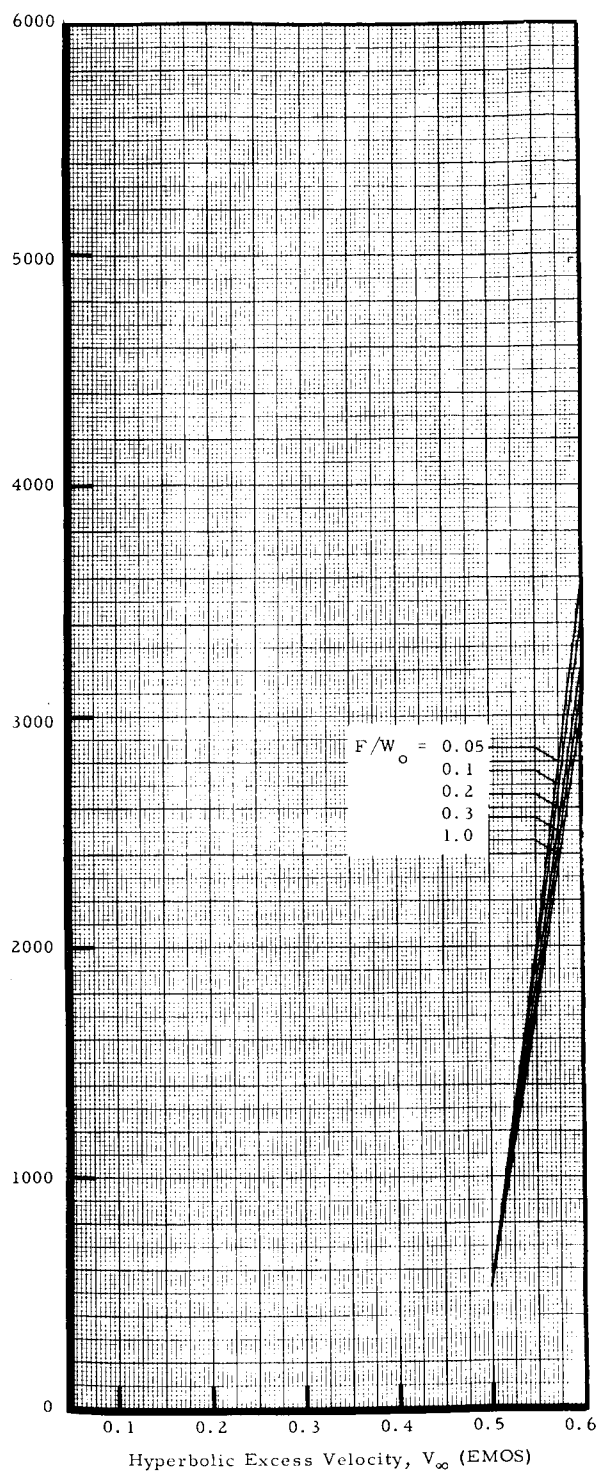


FIGURE 4c. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 340$  s  
 $(V_e)_{max} = 14000$  m/s



a.  $(V)_{e \max} = 16000 \text{ m/s}$



b.  $(V)_{e \max} = 18000 \text{ m/s}$

FIGURE 4d. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 340 \text{ s}$

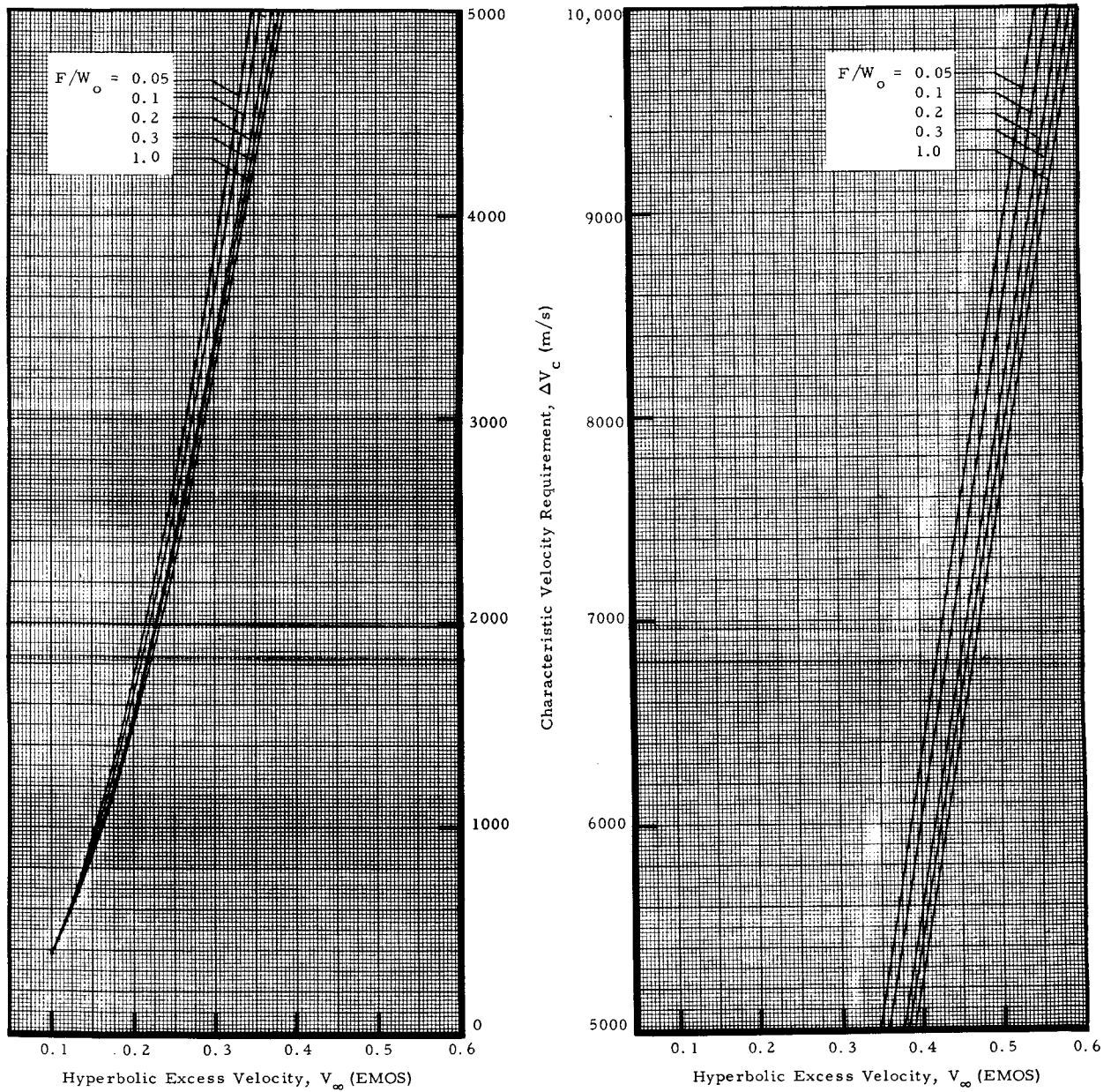


FIGURE 5a. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 420$  s  
 $(V_e)_{max} = 11030$  m/s



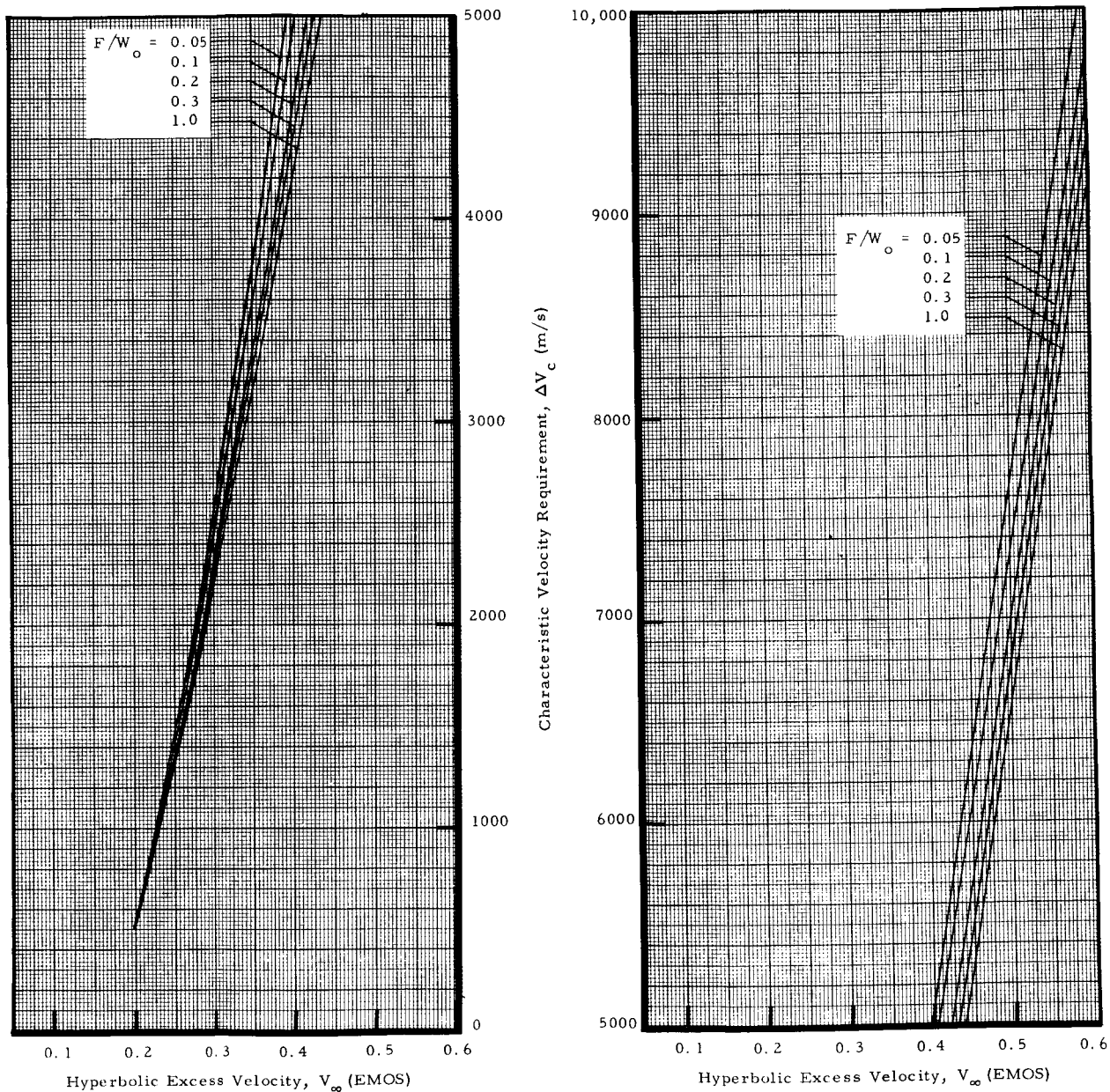


FIGURE 5b. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 420$  s  
 $(V_e)_{max} = 12000$  m/s

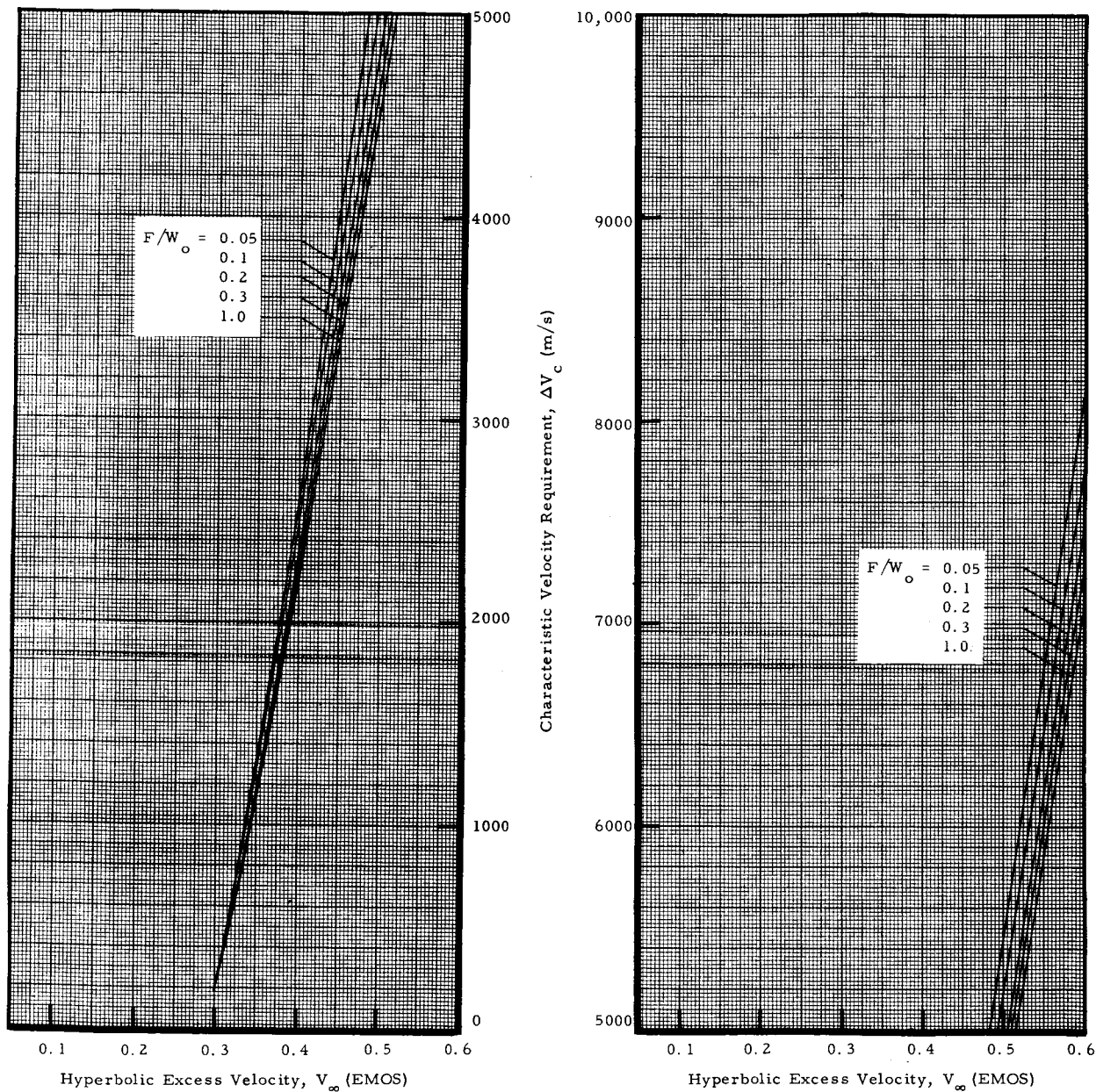
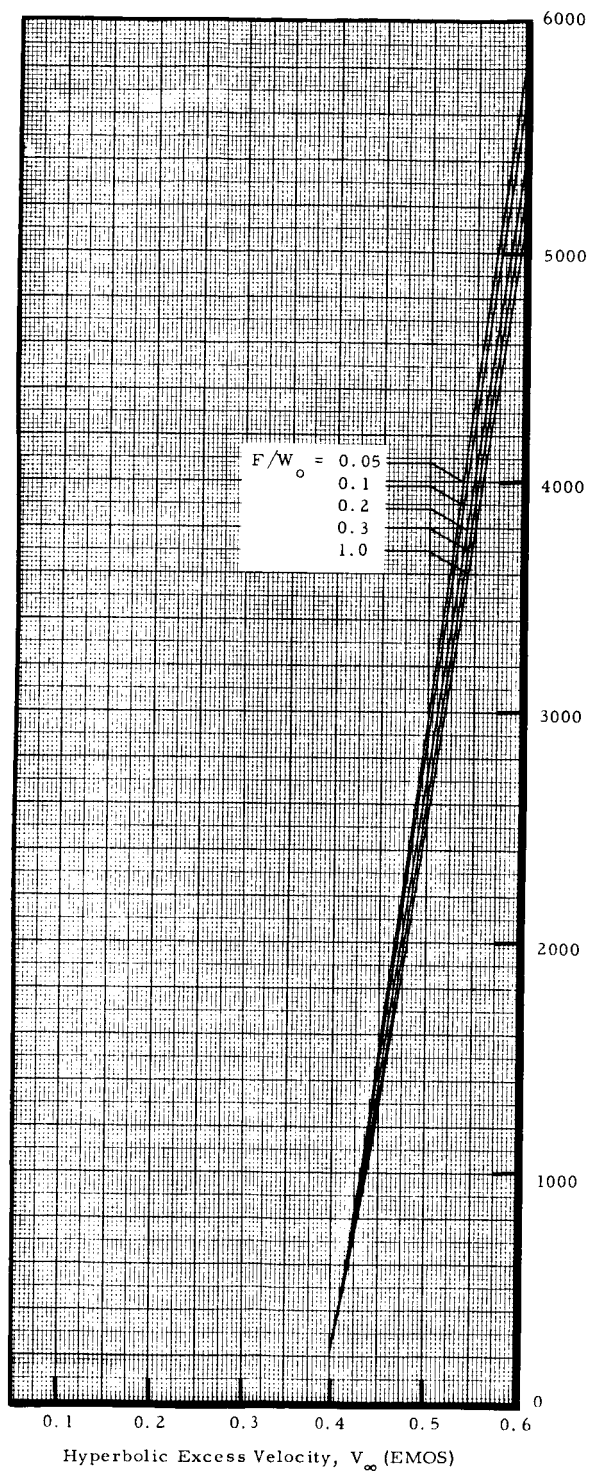
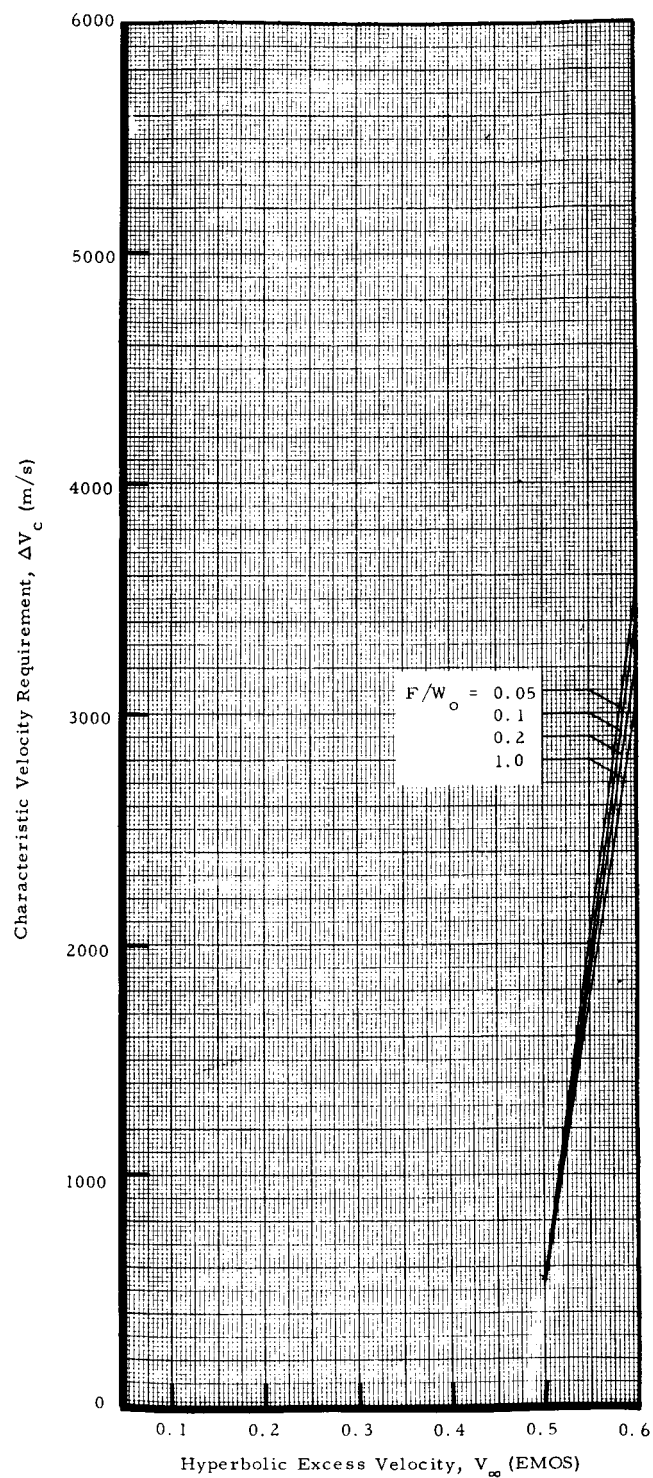


FIGURE 5c. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 420$  s  
 $(V_e)_{max} = 14000$  m/s



a.  $(V_e)_{\max} = 16000$  m/s



b.  $(V_e)_{\max} = 18000$  m/s

FIGURE 5d. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 420$  s



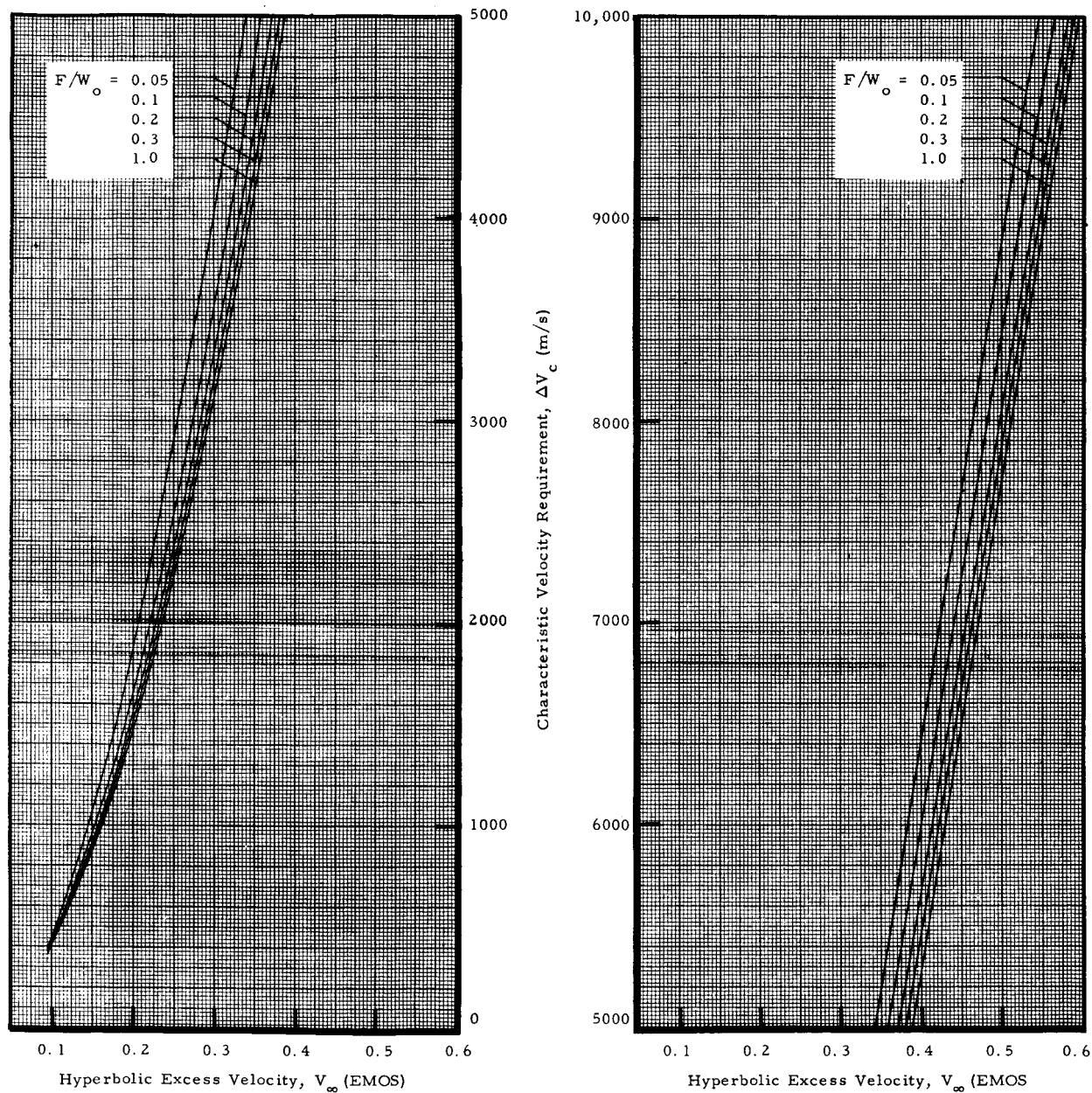


FIGURE 6a. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 430$  s  
 $(V_{e'})_{max} = 11030$  m/s

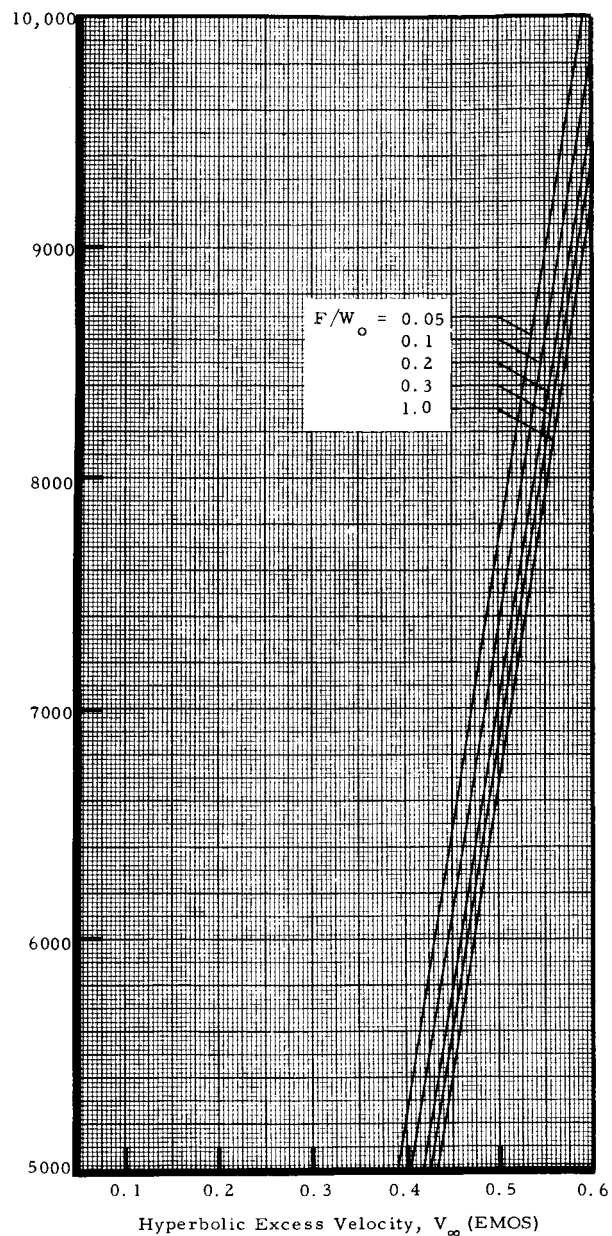
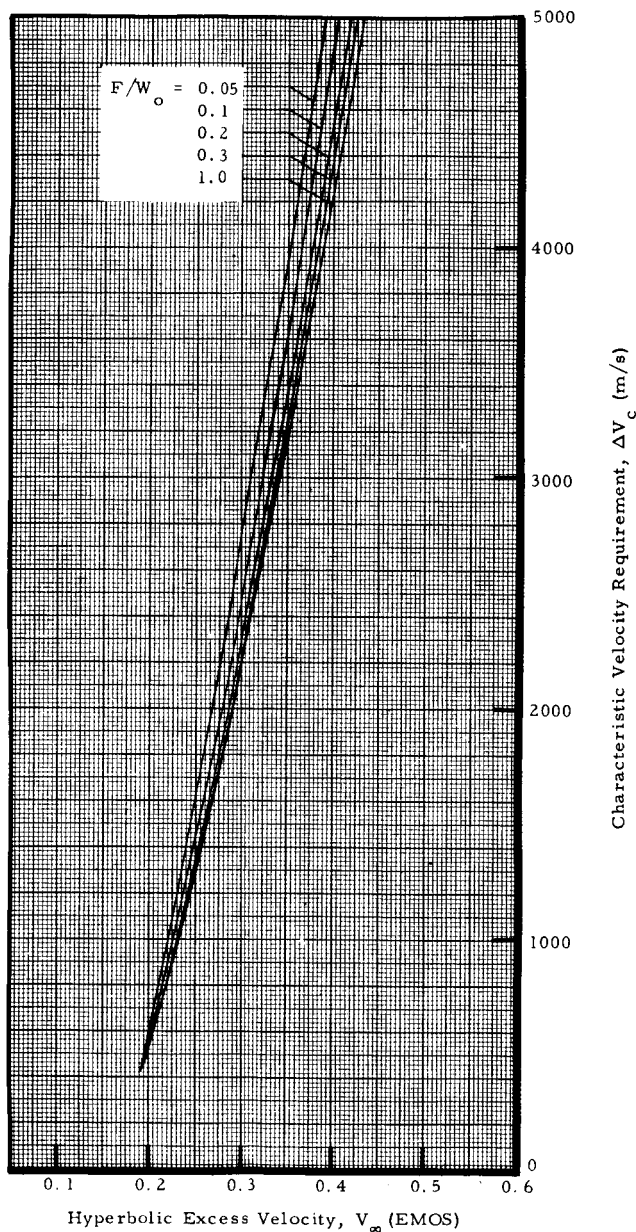


FIGURE 6b. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 430$  s  
 $(V_e)_{max} = 12000$  m/s

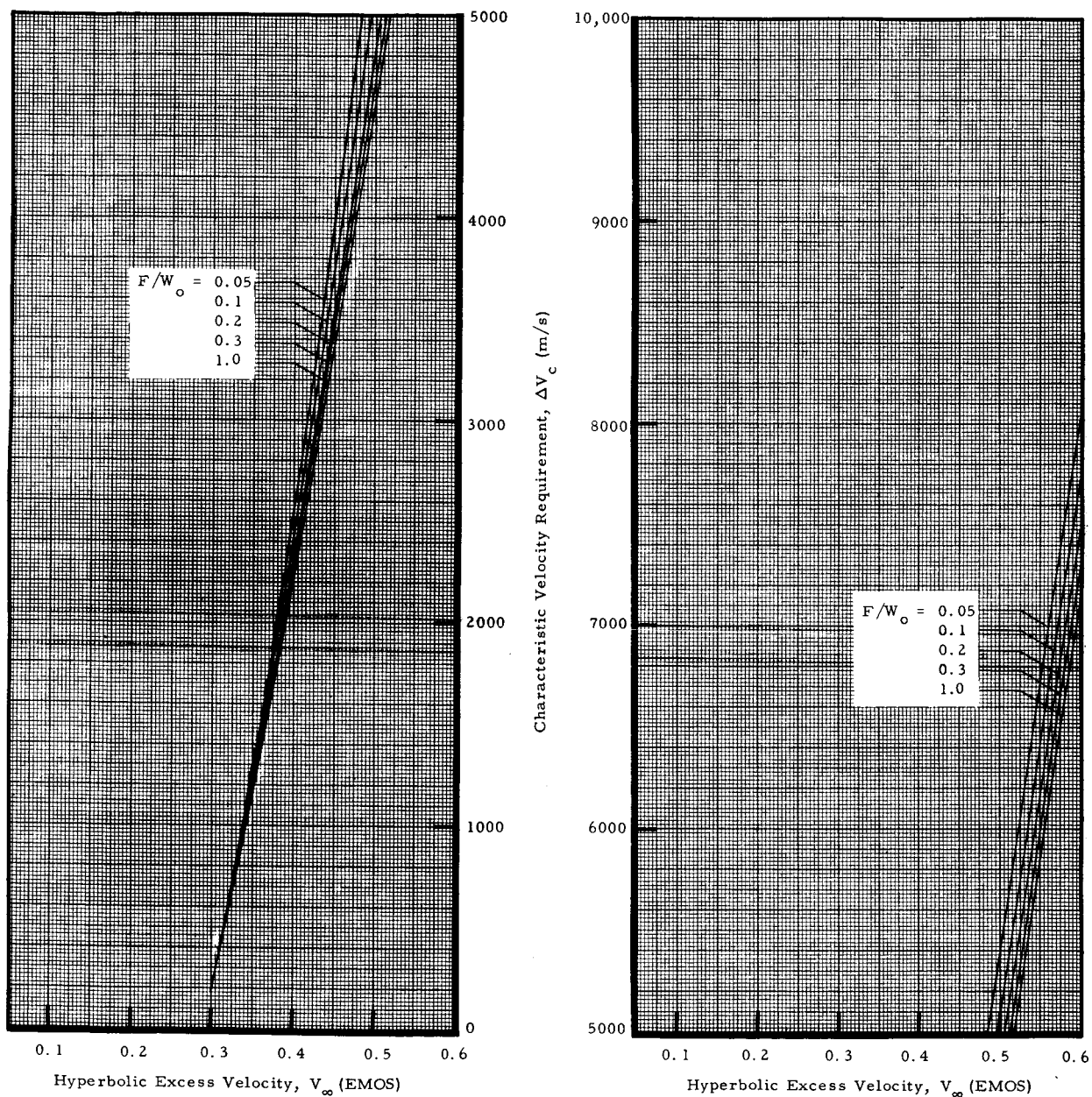
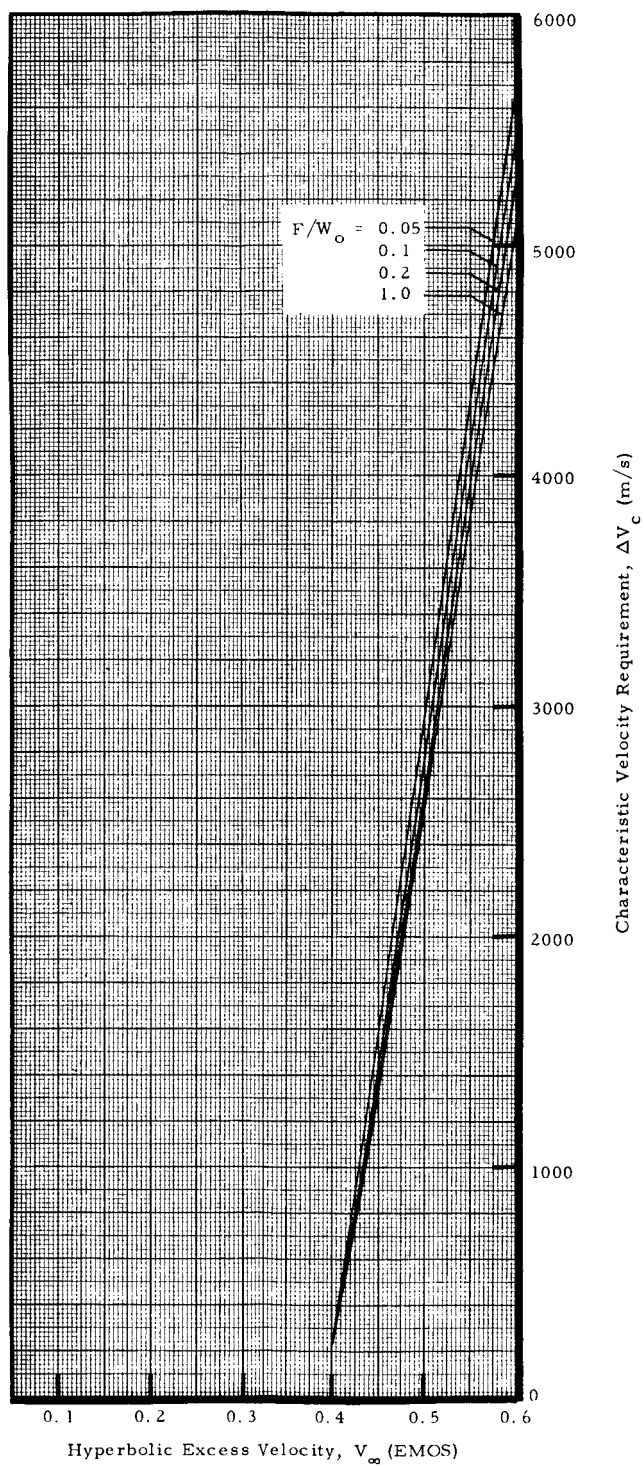
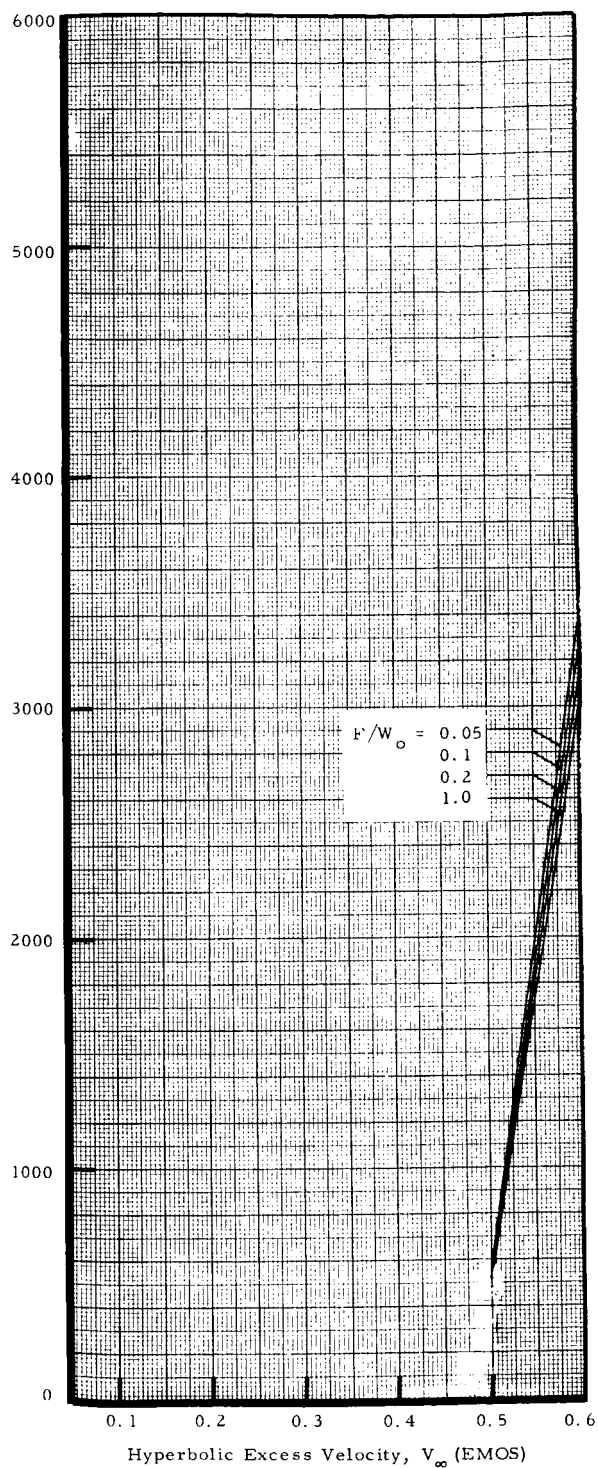


FIGURE 6c. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 430$  s  
 $(V_e)_{max} = 14000$  m/s



a.  $(V_e)_{\max} = 16000$  m/s



b.  $(V_e)_{\max} = 18000$  m/s

FIGURE 6d. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 430$  s

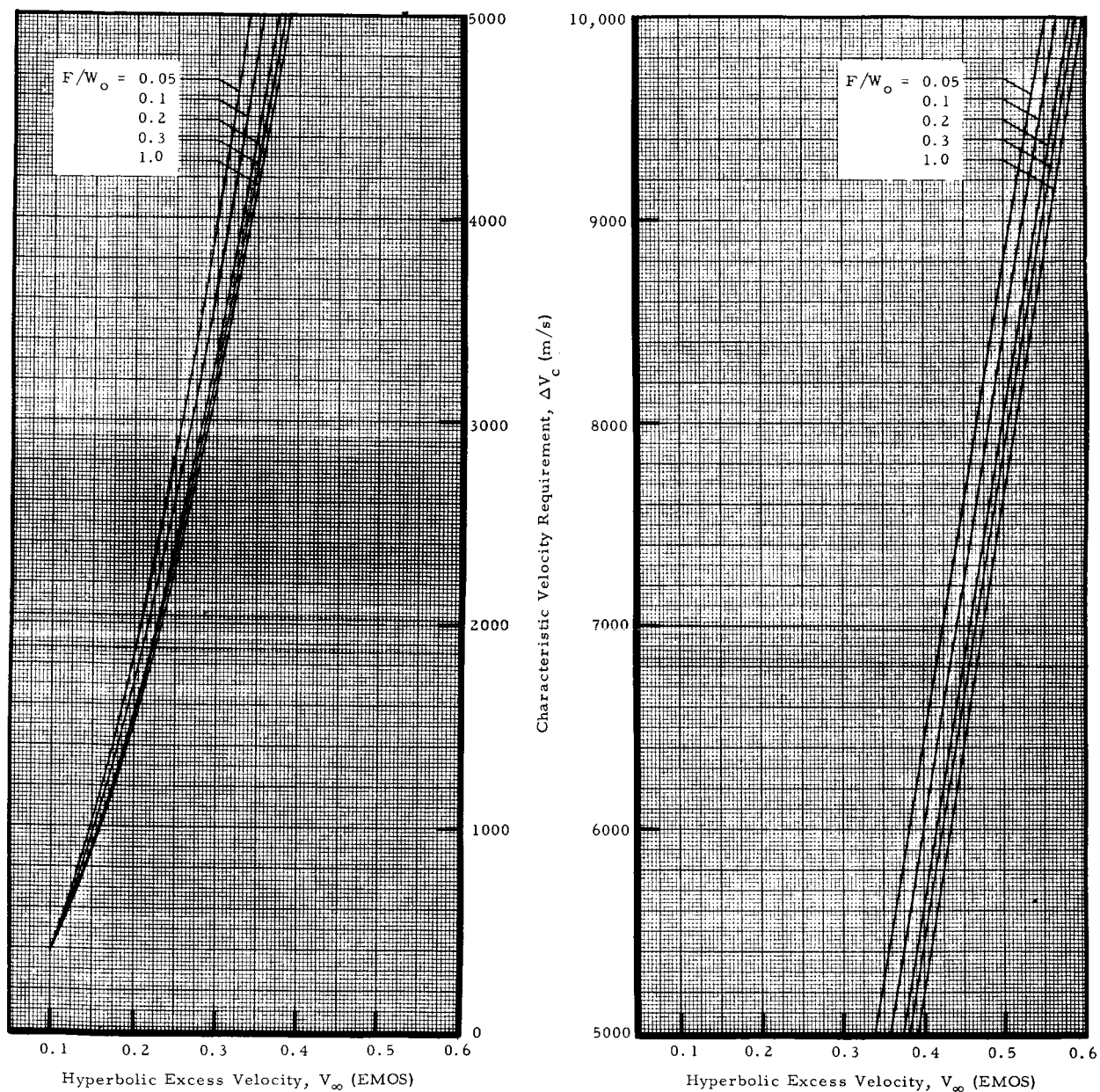


FIGURE 7a. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 440$  s  
 $(V_e)_{max} = 11030$  m/s



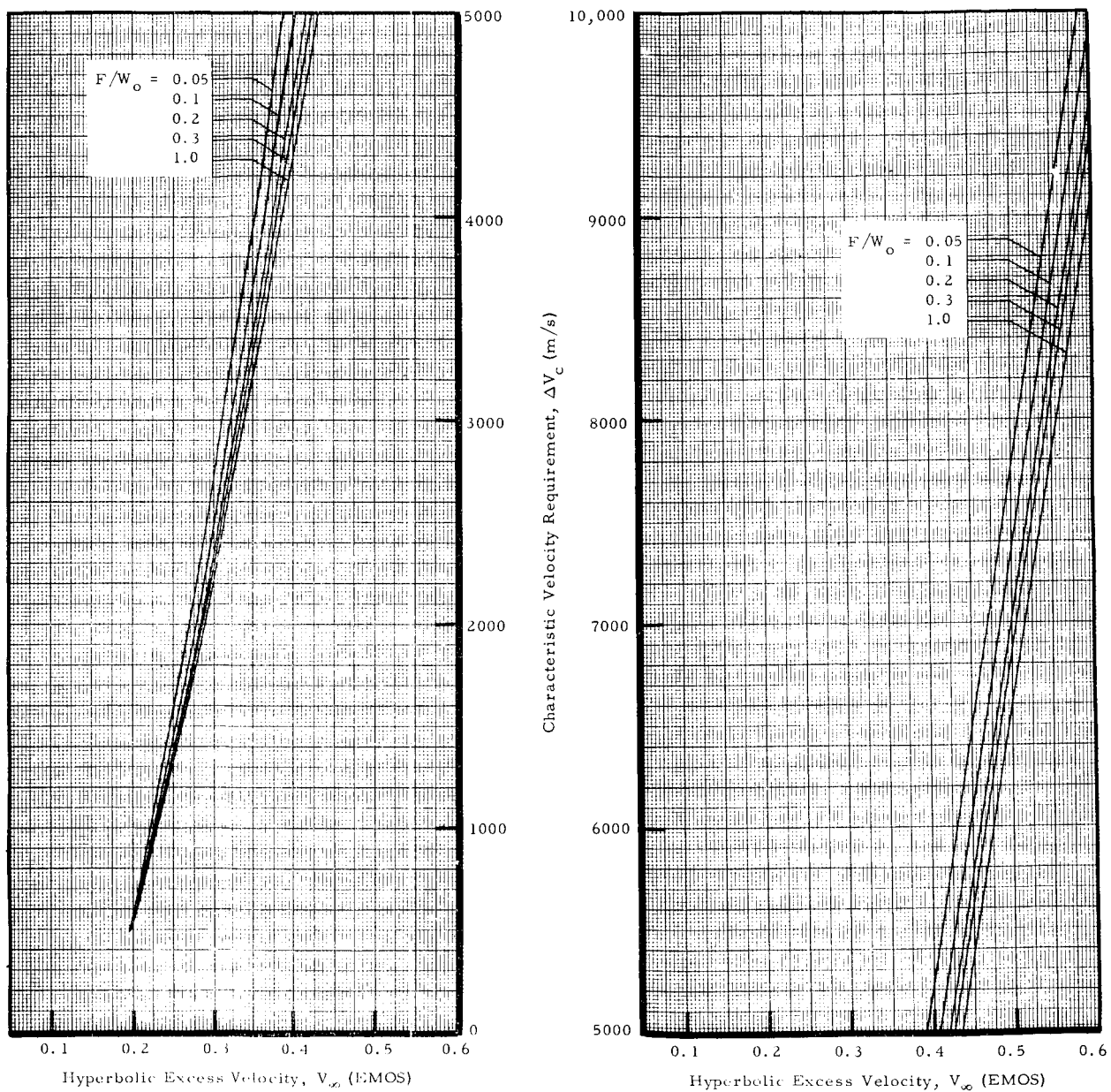


FIGURE 7b. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 440$  s  
 $(V_c)_{max} = 12000$  m/s

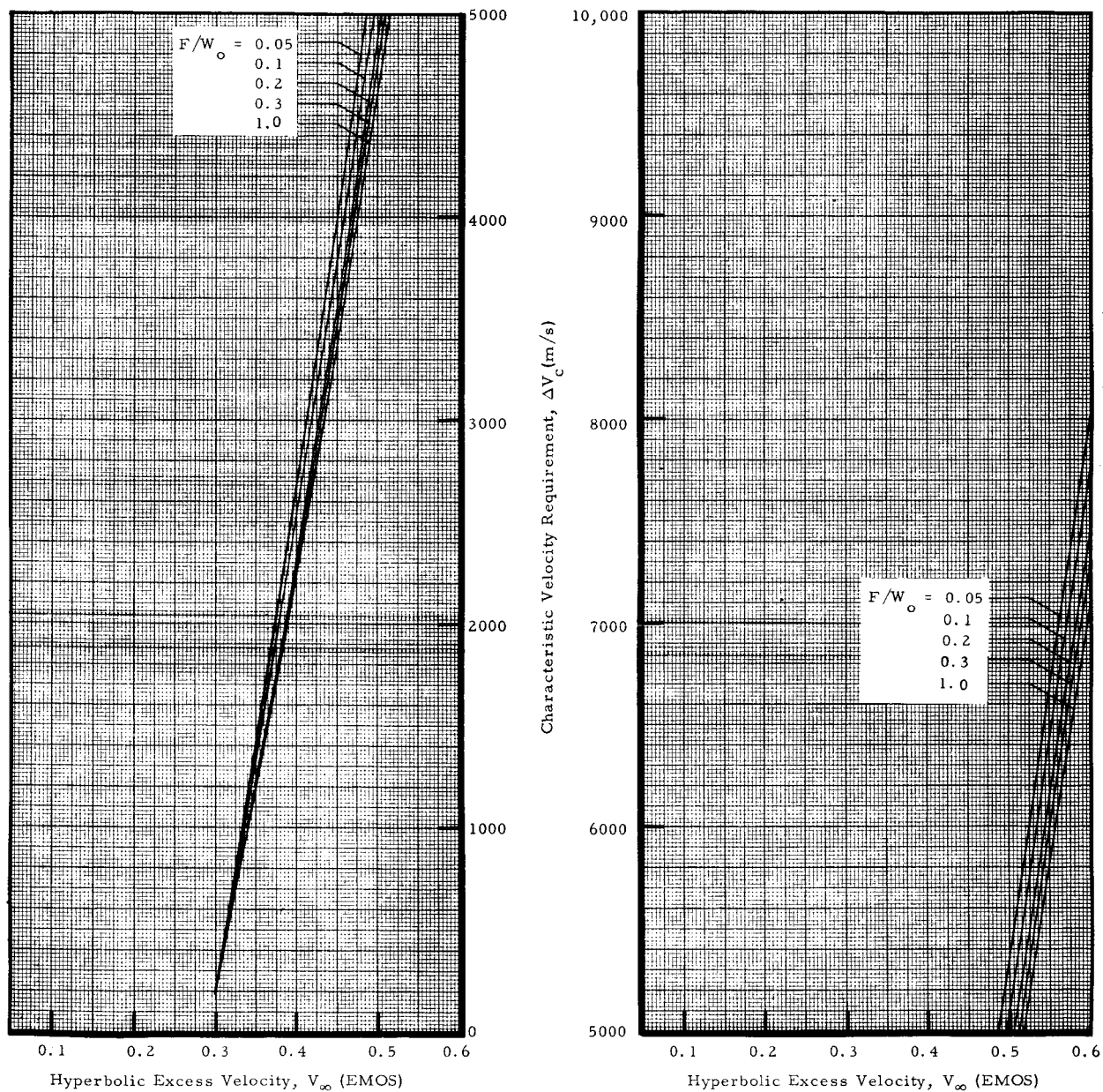
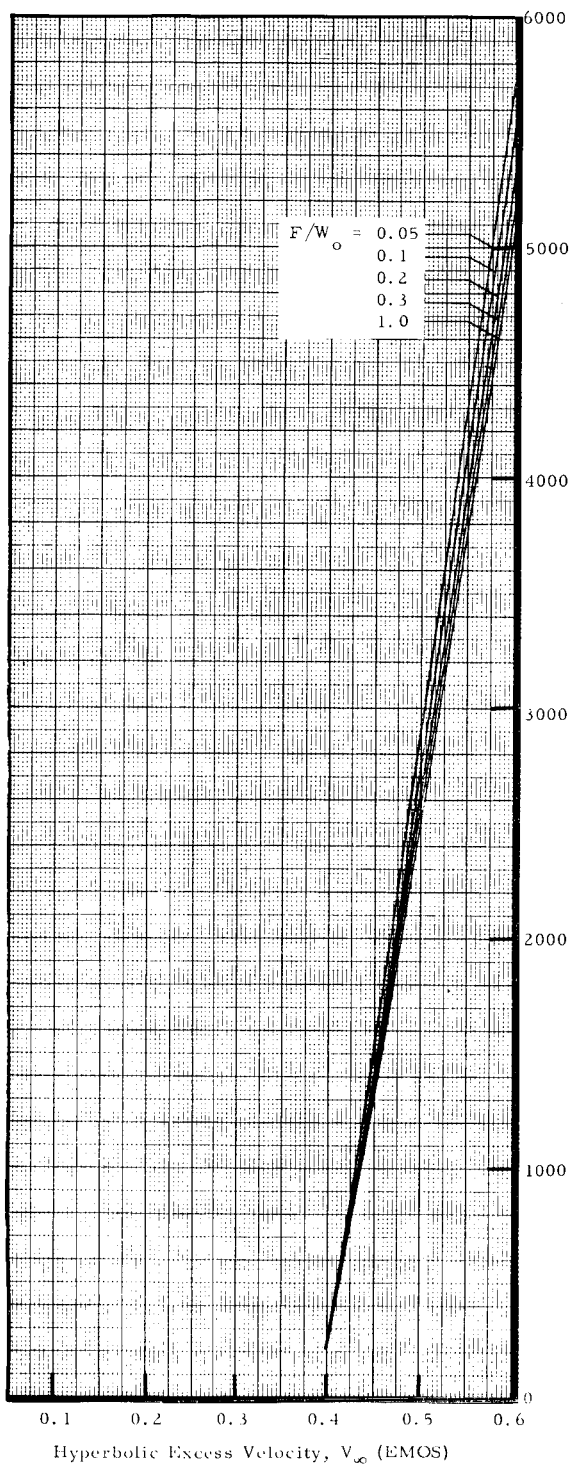
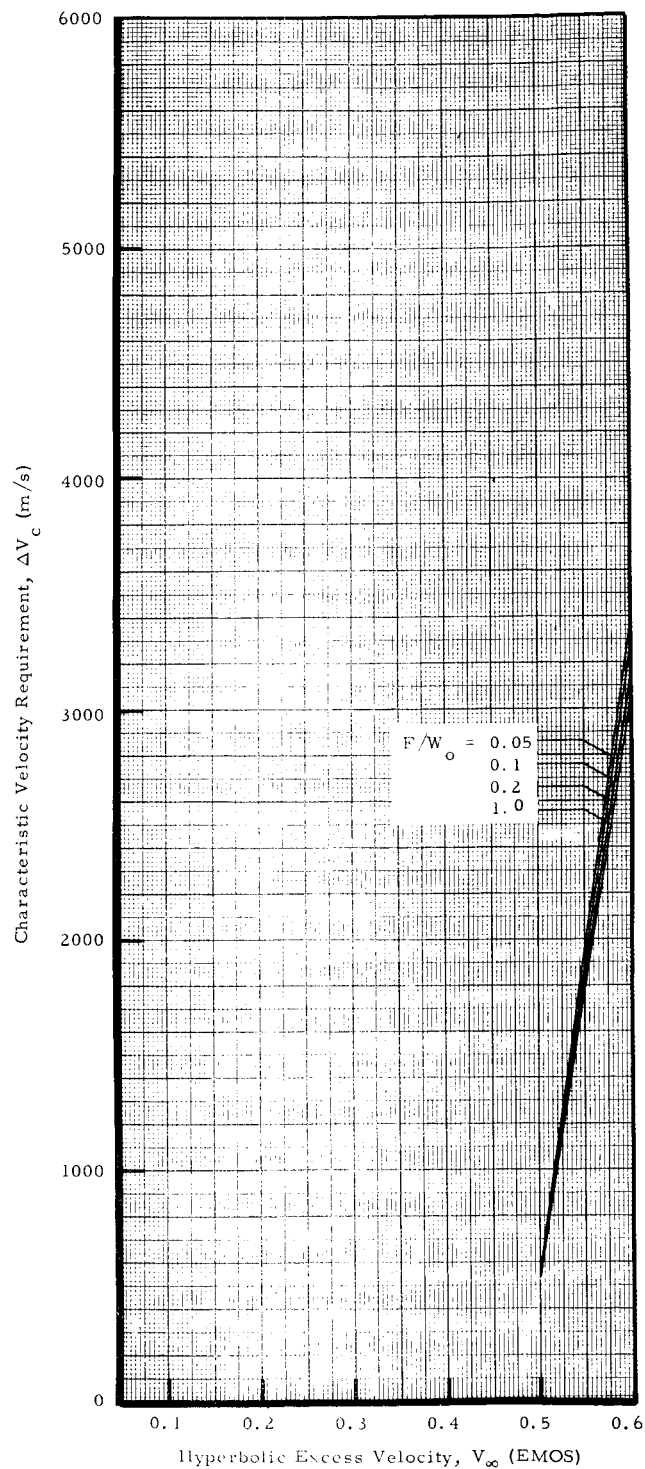


FIGURE 7c. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 440$  s  
 $(V_e)_{max} = 14000$  m/s



a.  $(V_e)_{\max} = 16000$  m/s



b.  $(V_e)_{\max} = 18000$  m/s

FIGURE 7d. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 440$  s



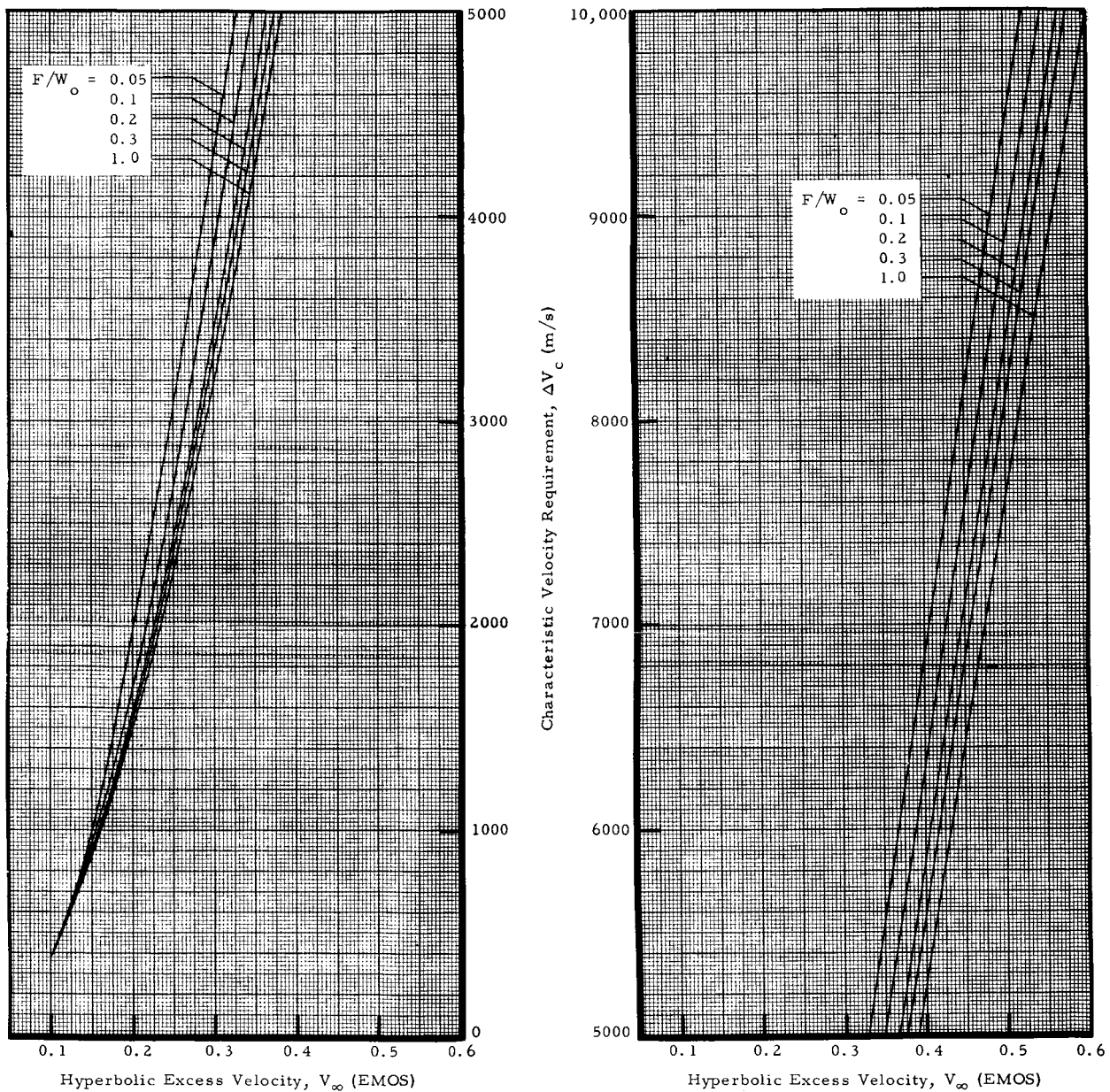


FIGURE 8a. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 775$  s  
 $(V_e)_{max} = 11030$  m/s

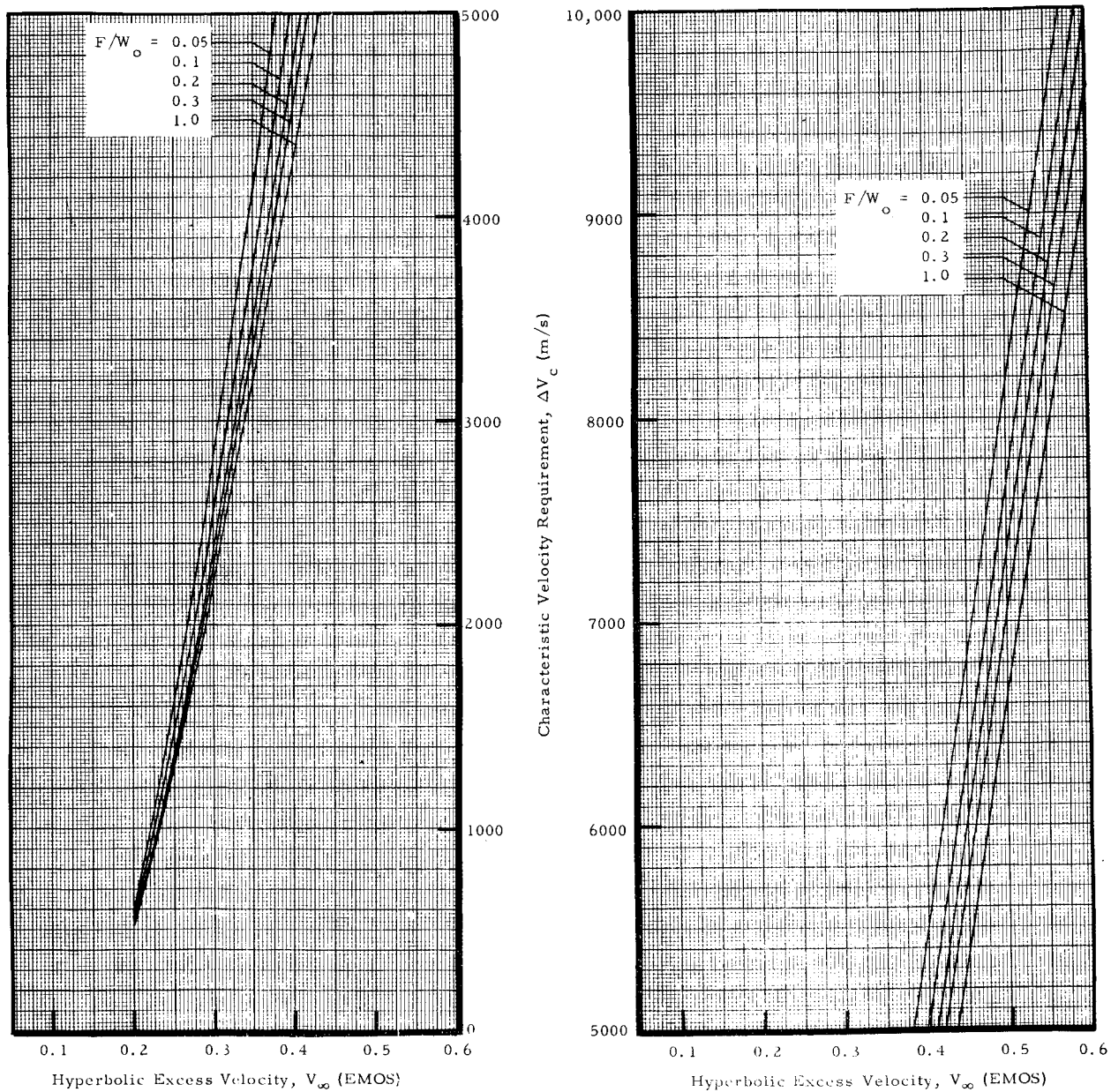


FIGURE 8b. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 775$  s  
 $(V_e)_{max} = 12000$  m/s

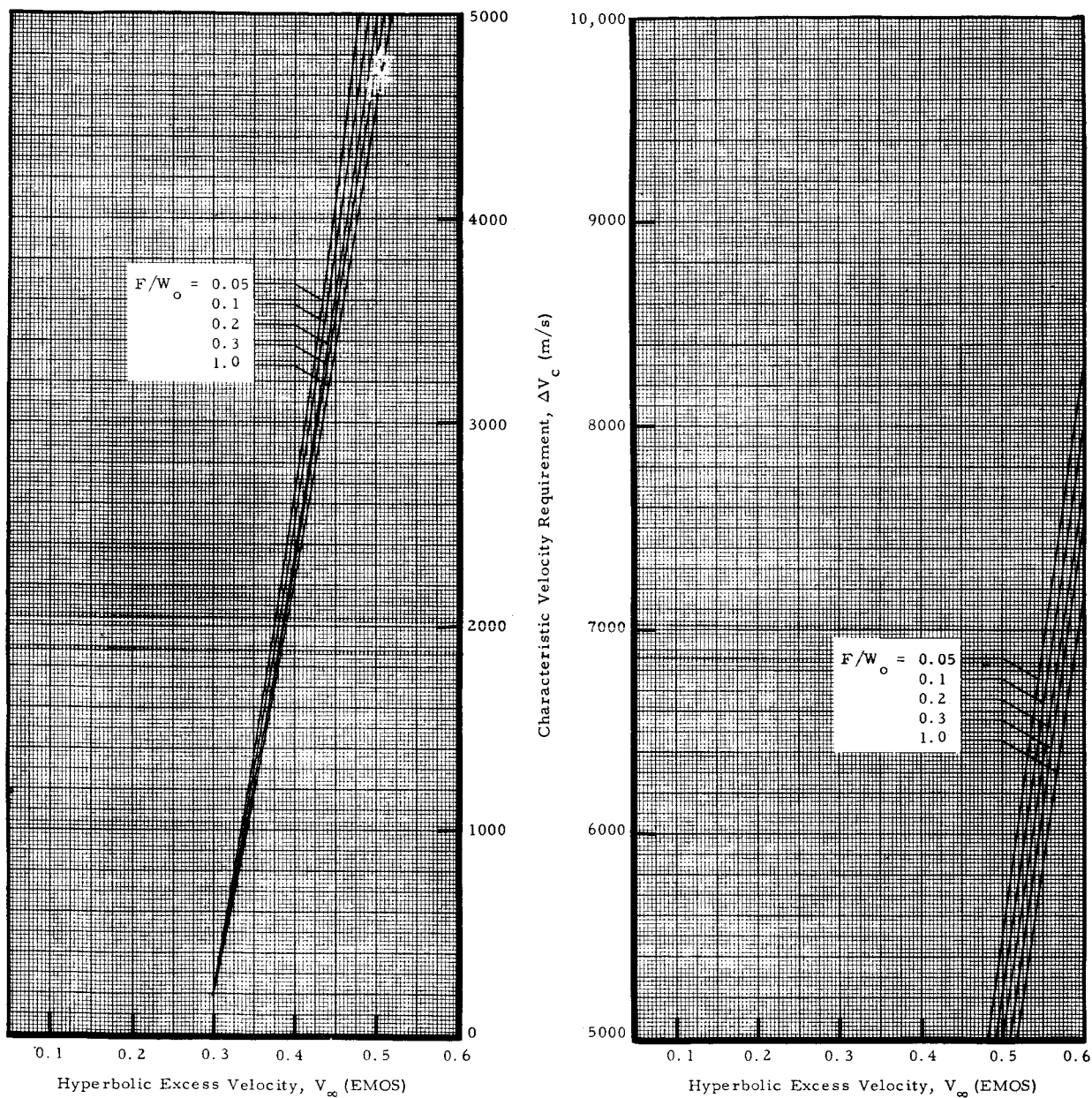
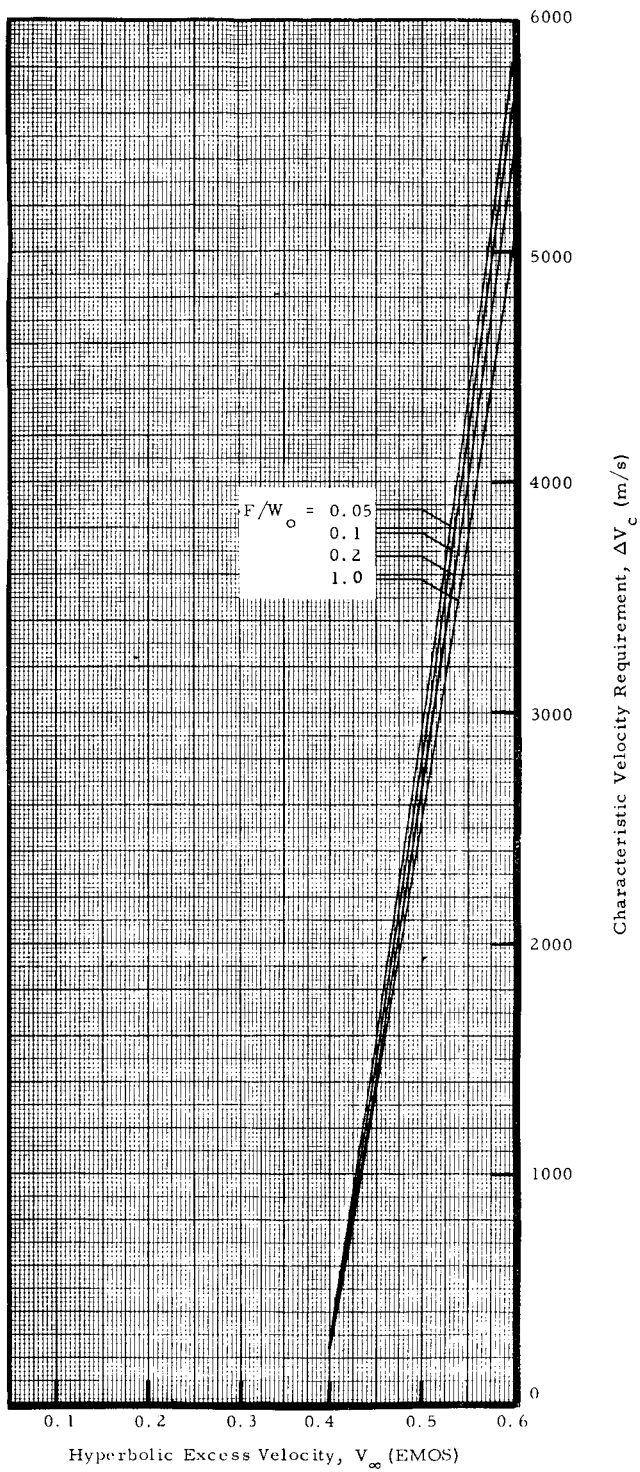
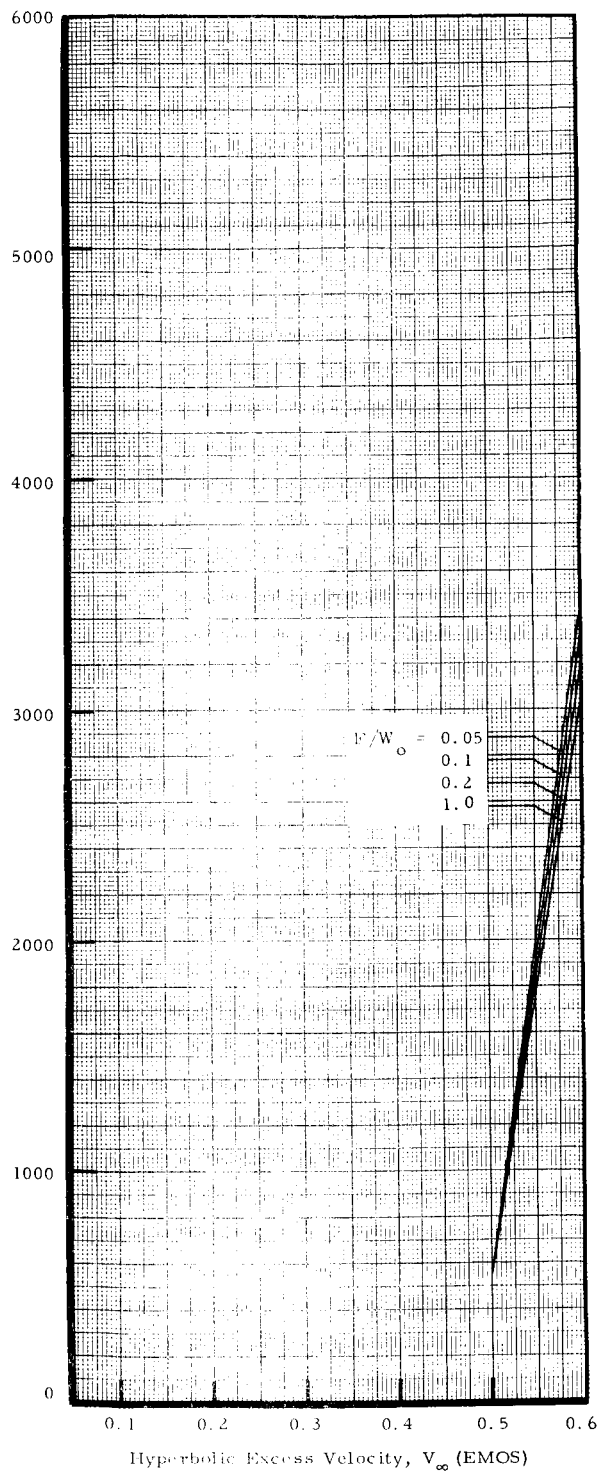


FIGURE 8c. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 775$  s  
 $(V_e)_{max} = 14000$  m/s



a.  $(V_e)_{\max} = 16000$  m/s



b.  $(V_e)_{\max} = 18000$  m/s

FIGURE 8d. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 775$  s

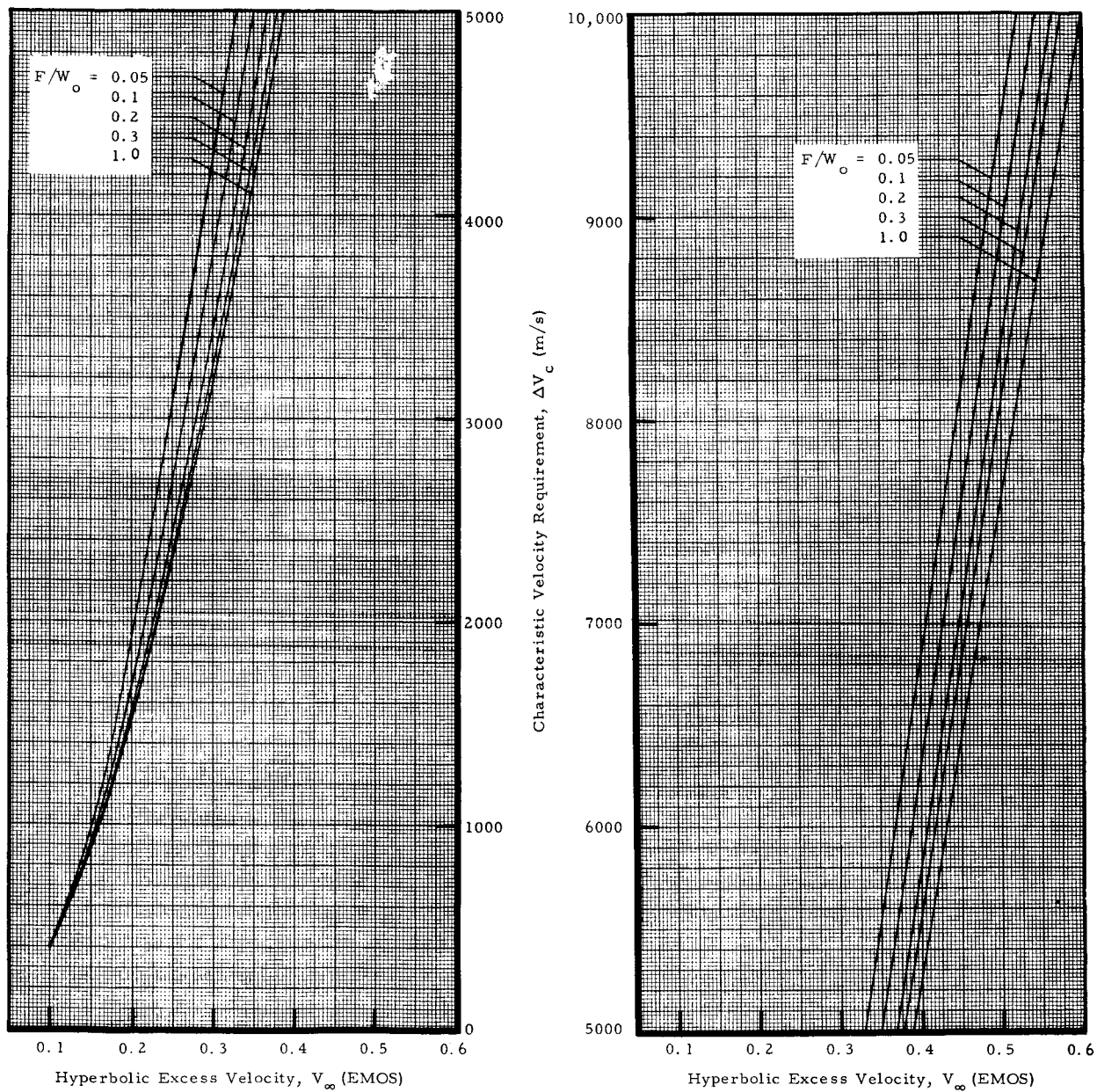


FIGURE 9a. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 800$  s  
 $(V_e)_{max} = 11030$  m/s



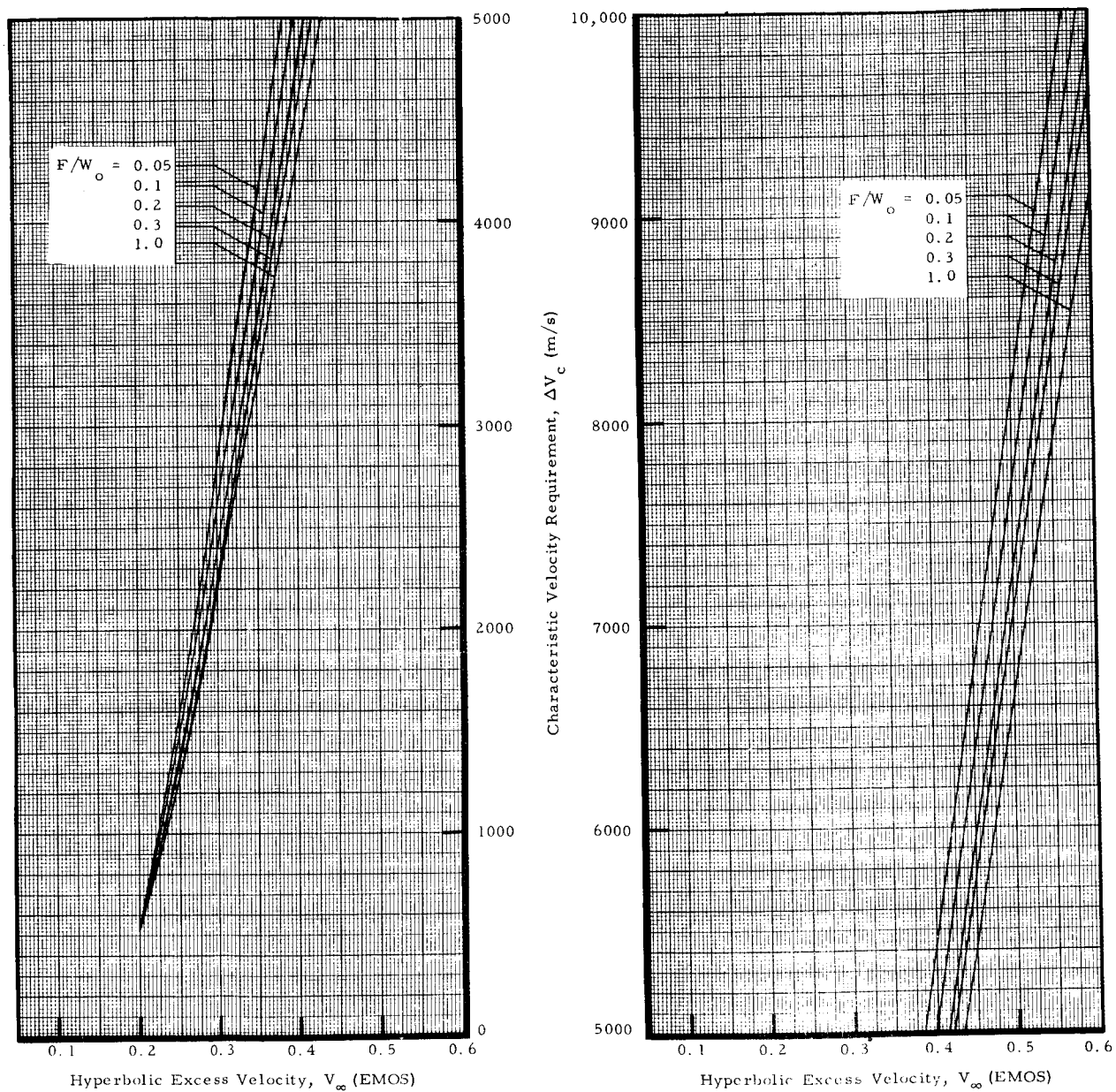


FIGURE 9b. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 800$  s  
 $(V_e)_{max} = 12000$  m/s

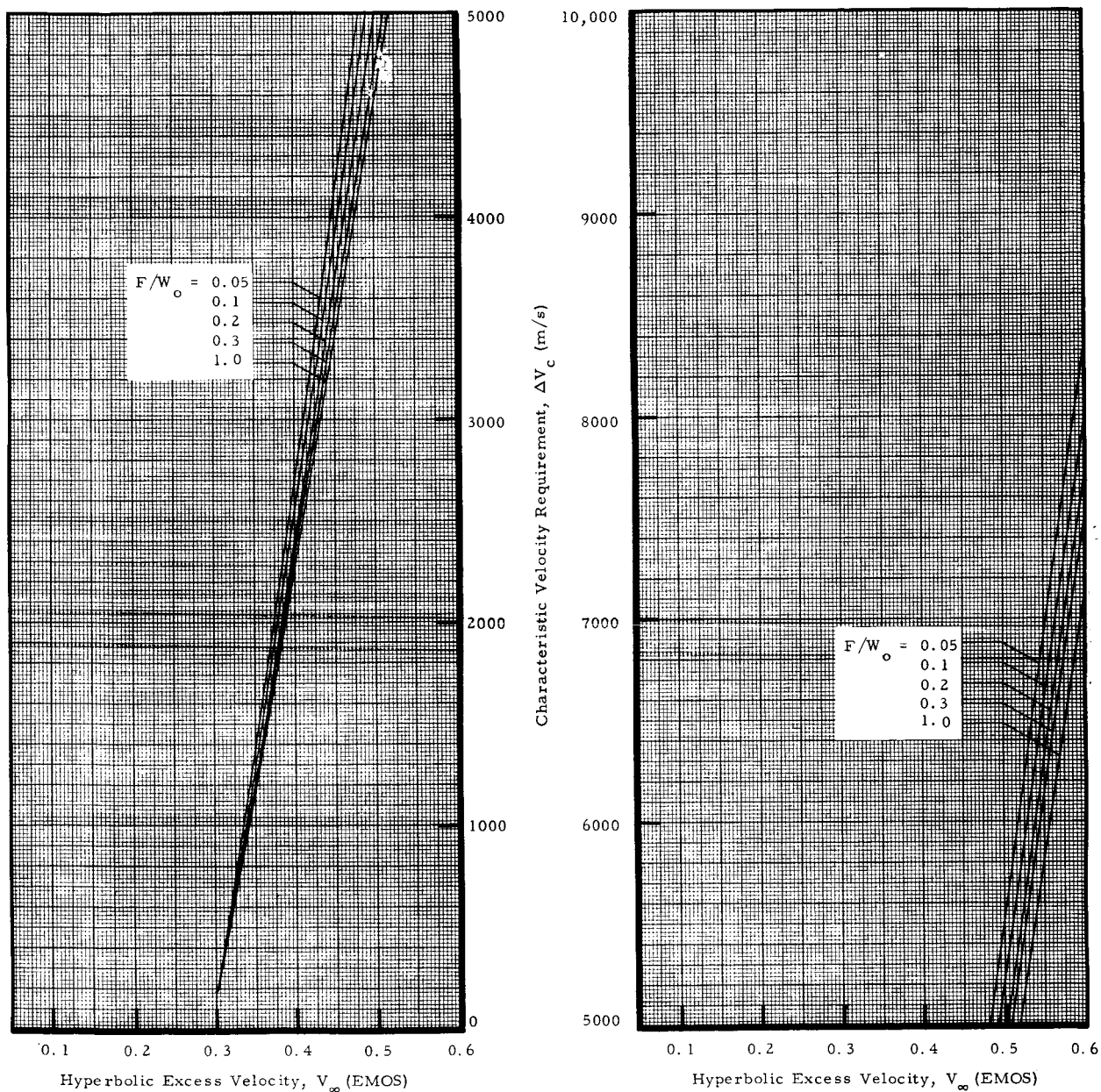
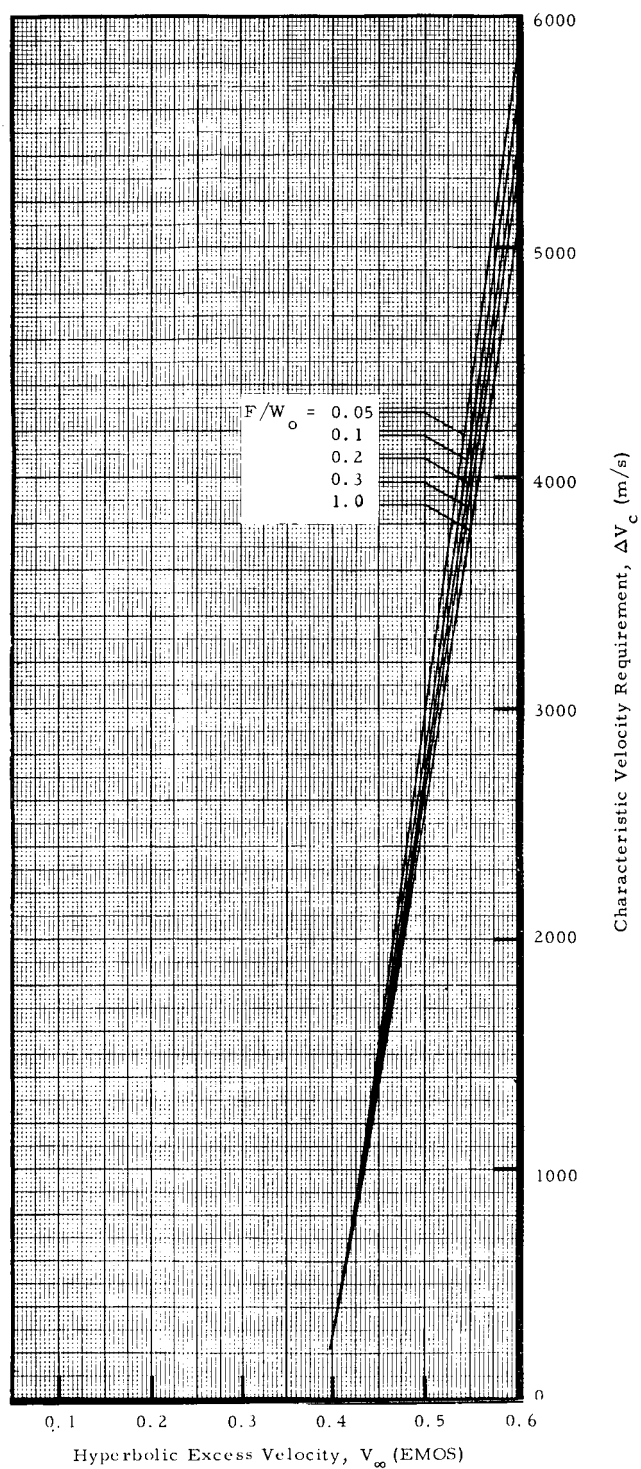
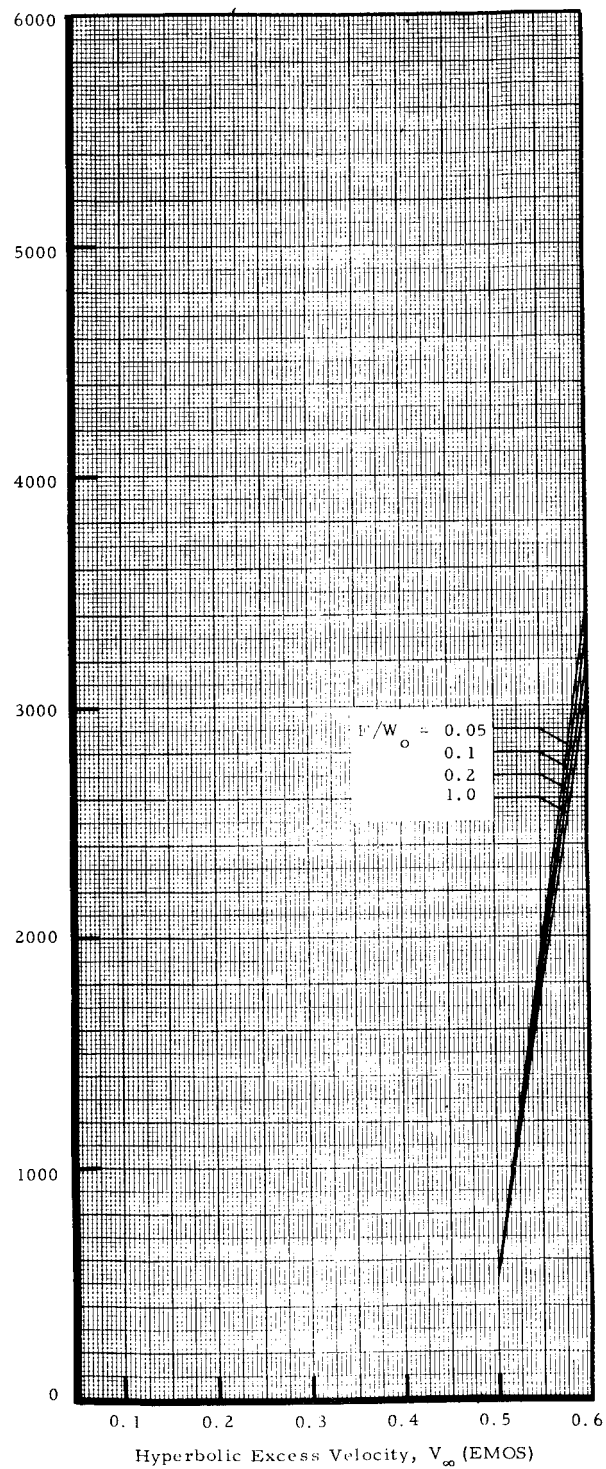


FIGURE 9c. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 800$  s  
 $(V_e)_{max} = 14000$  m/s



a.  $(V_e)_{\max} = 16000$  m/s



b.  $(V_e)_{\max} = 18000$  m/s

FIGURE 9d. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 800$  s



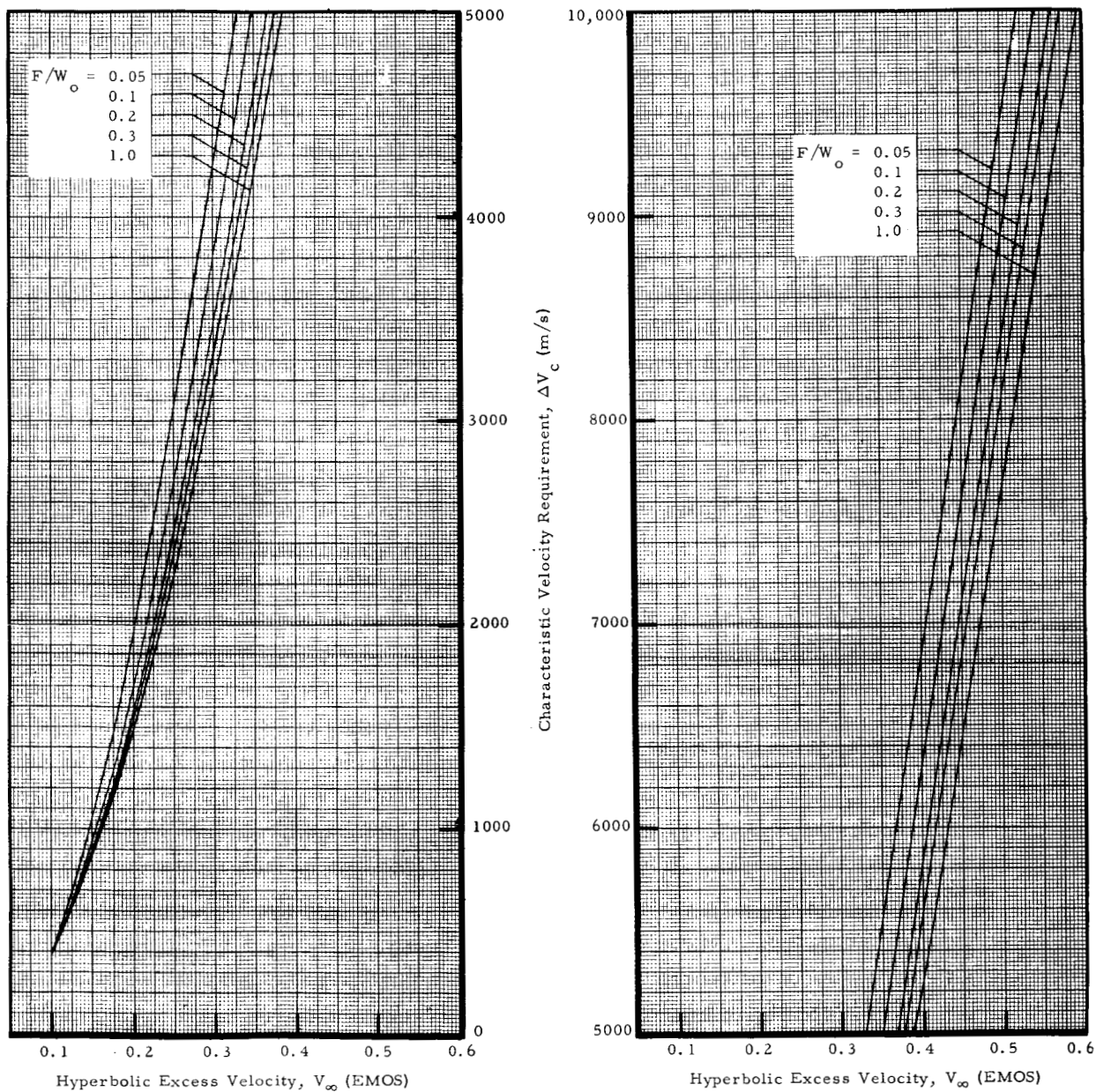


FIGURE 10a. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 825$  s  
 $(V_e)_{max} = 11030$  m/s

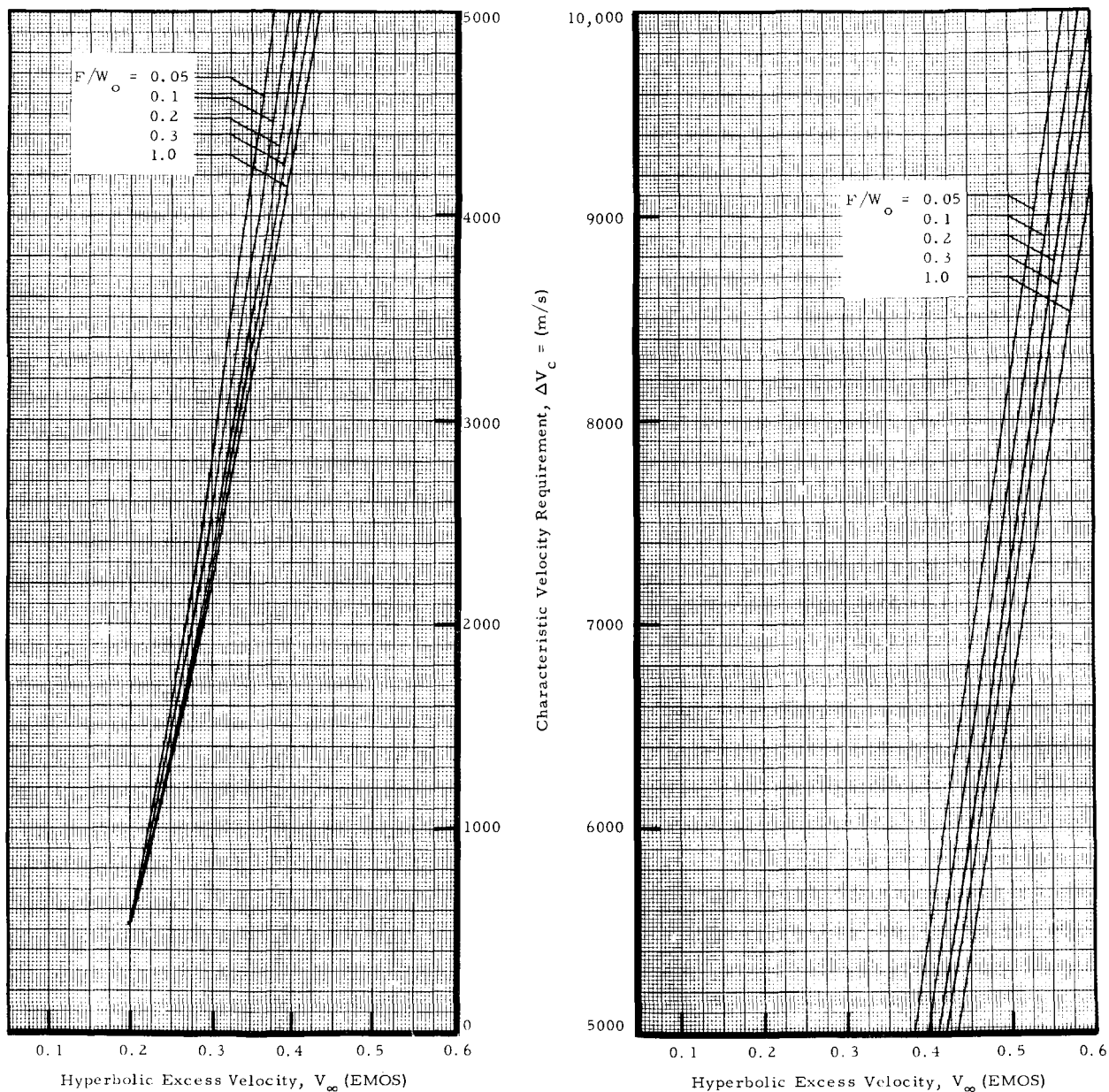


FIGURE 10b. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 825$  s  
 $(V_e)_{max} = 12000$  m/s

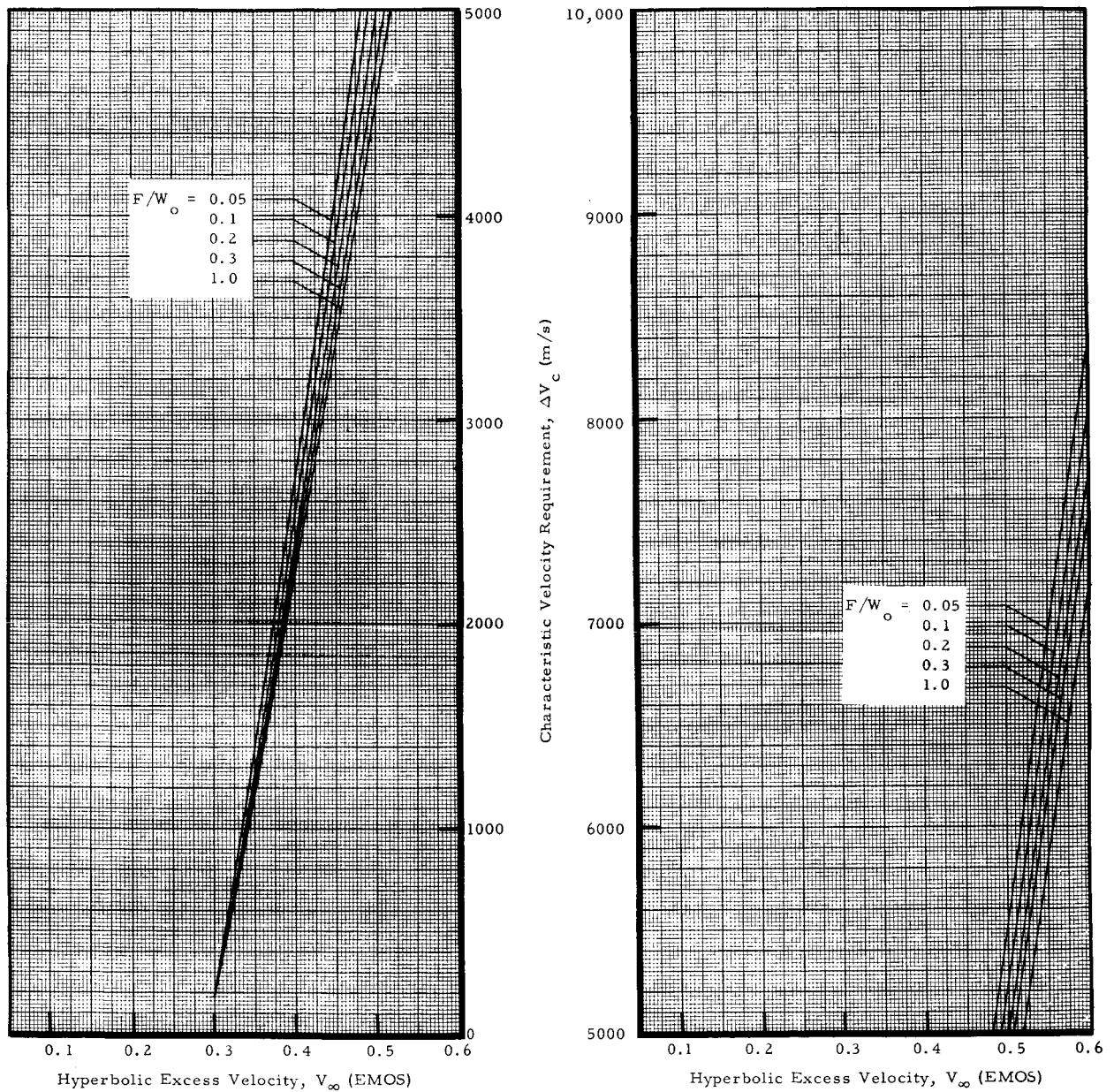


FIGURE 10c. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 825$  s  
 $(V_e)_{max} = 14000$  m/s

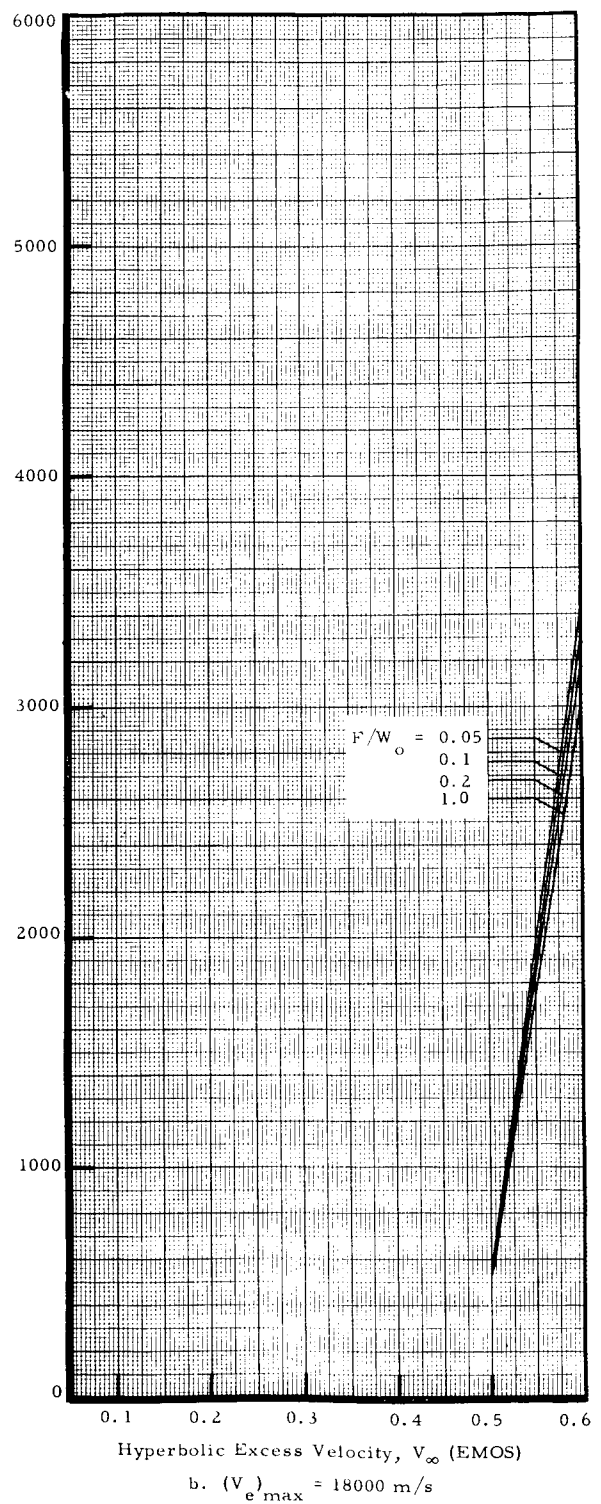
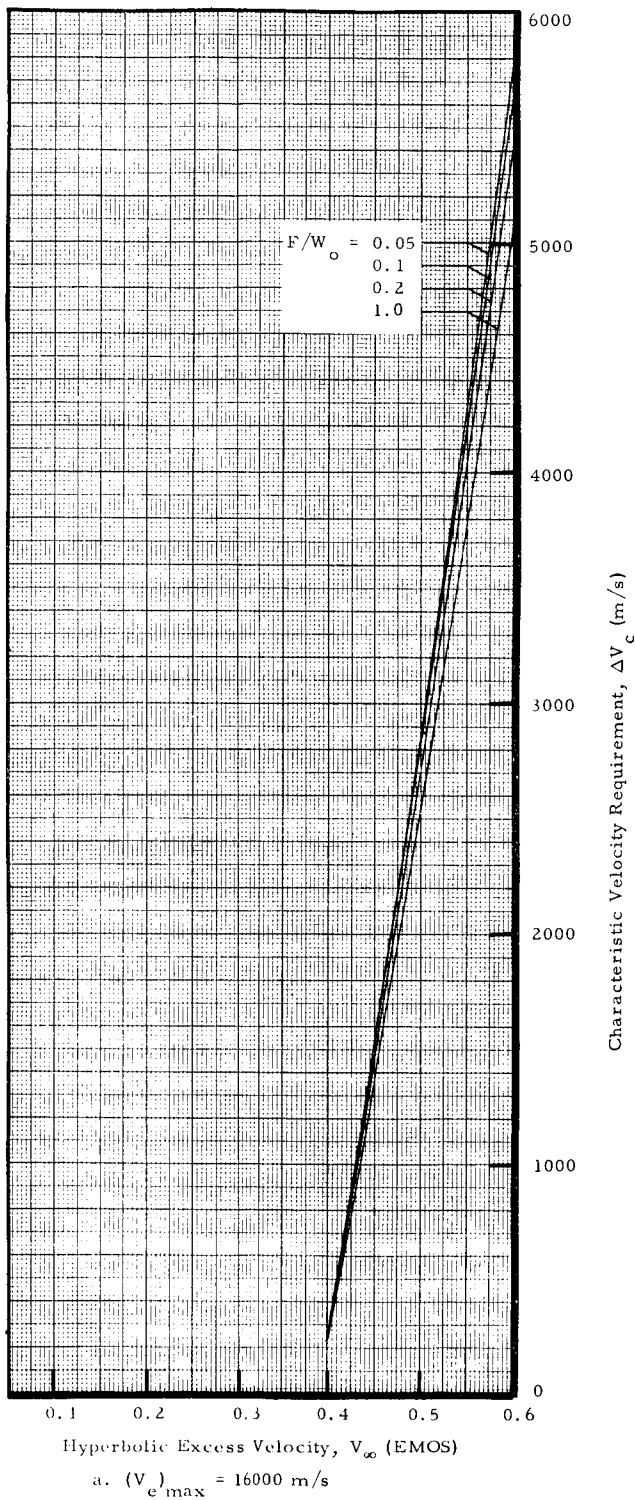


FIGURE 10d. EARTH REENTRY CHARACTERISTIC VELOCITY REQUIREMENTS FOR  $I_{sp} = 825$  s

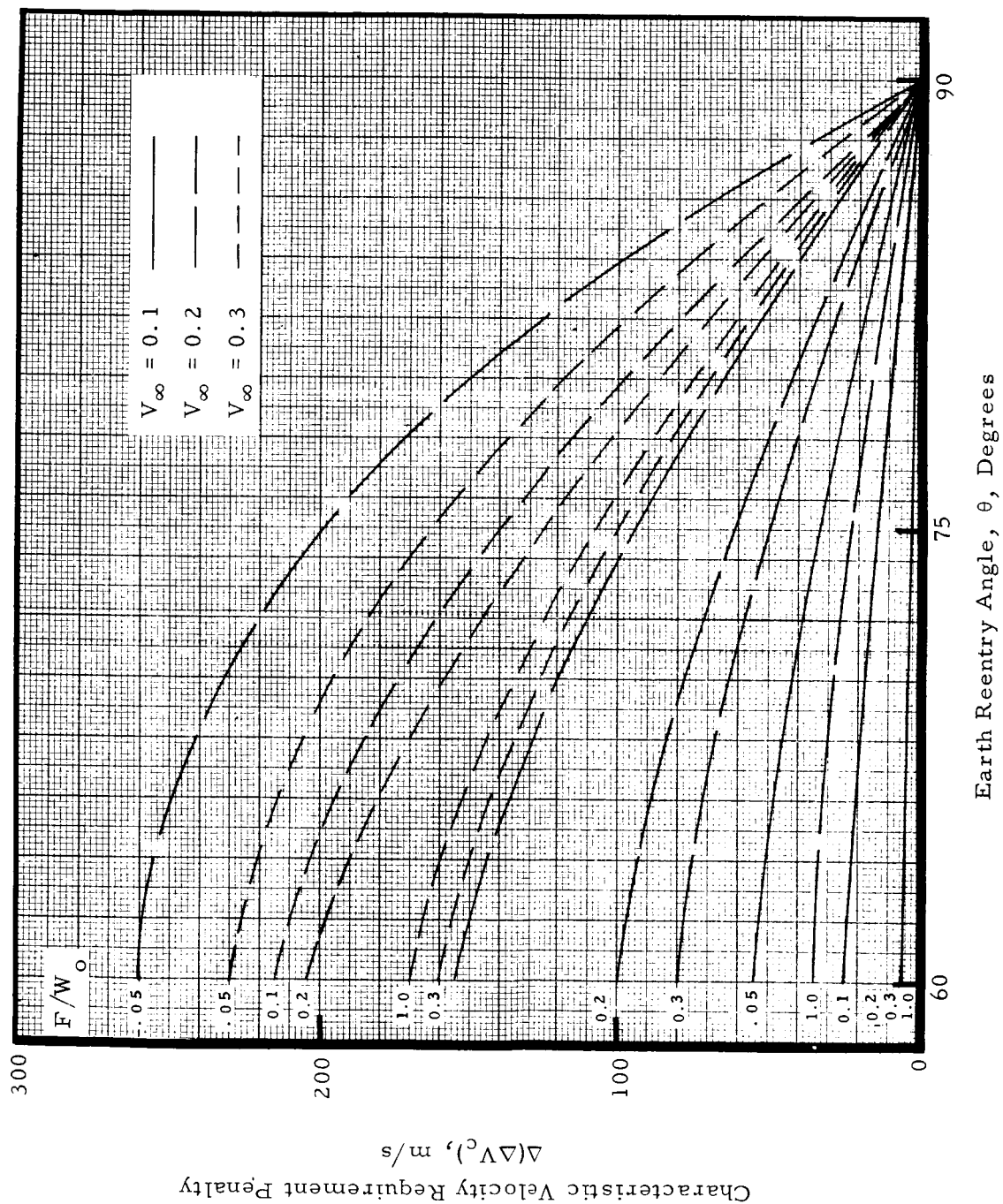


FIGURE 11a. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR  $\theta_{REF} = 90^\circ$   
 $I_{sp} = 330 \text{ sec}$   $(V_e)_{max} = 11030 \text{ m/s}$

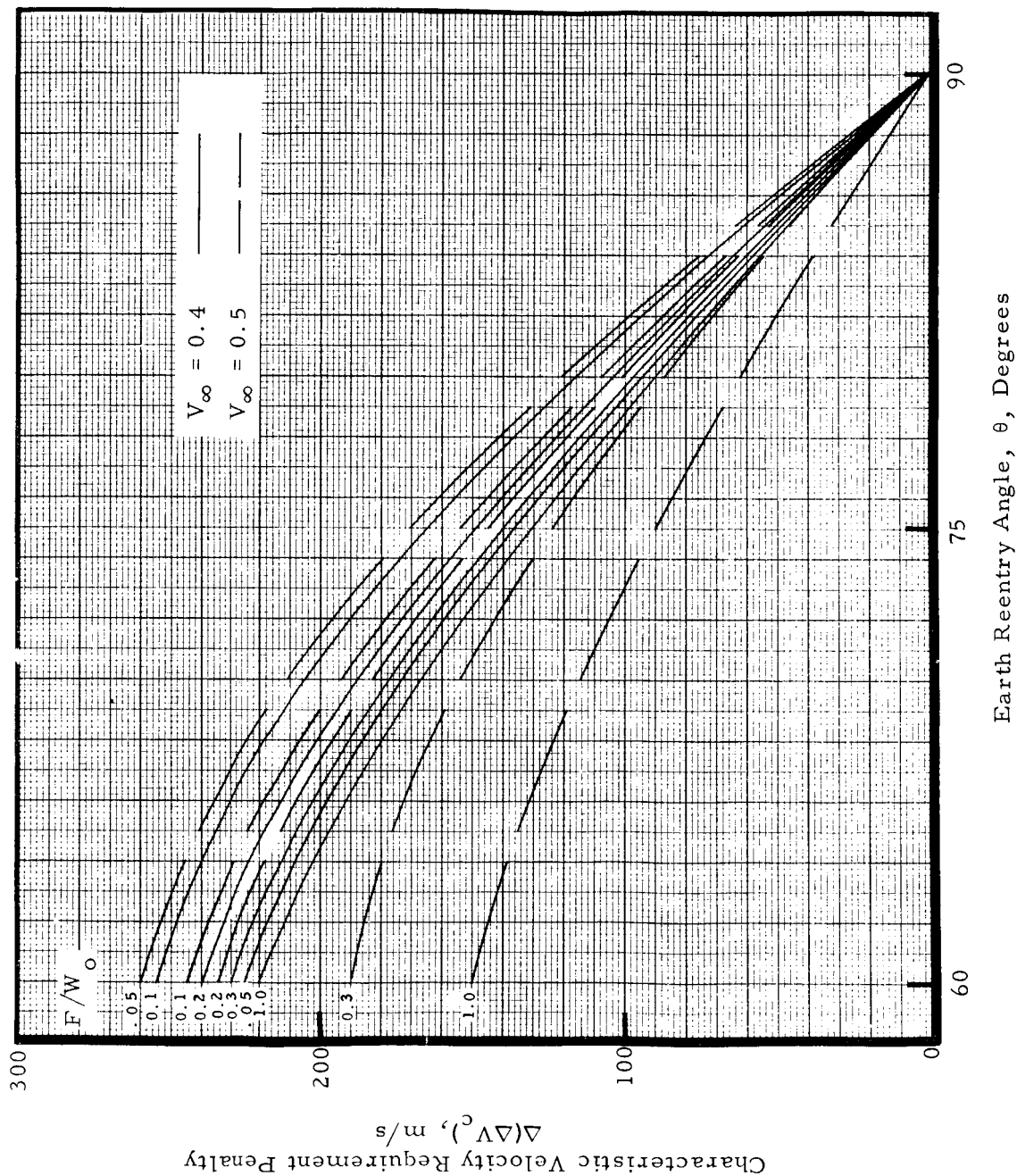


FIGURE 11b. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR  $\theta_{REF} = 90^\circ$

$$I_{sp} = 330 \text{ sec}$$

$$(V_e)_{max} = 11030 \text{ m/s}$$



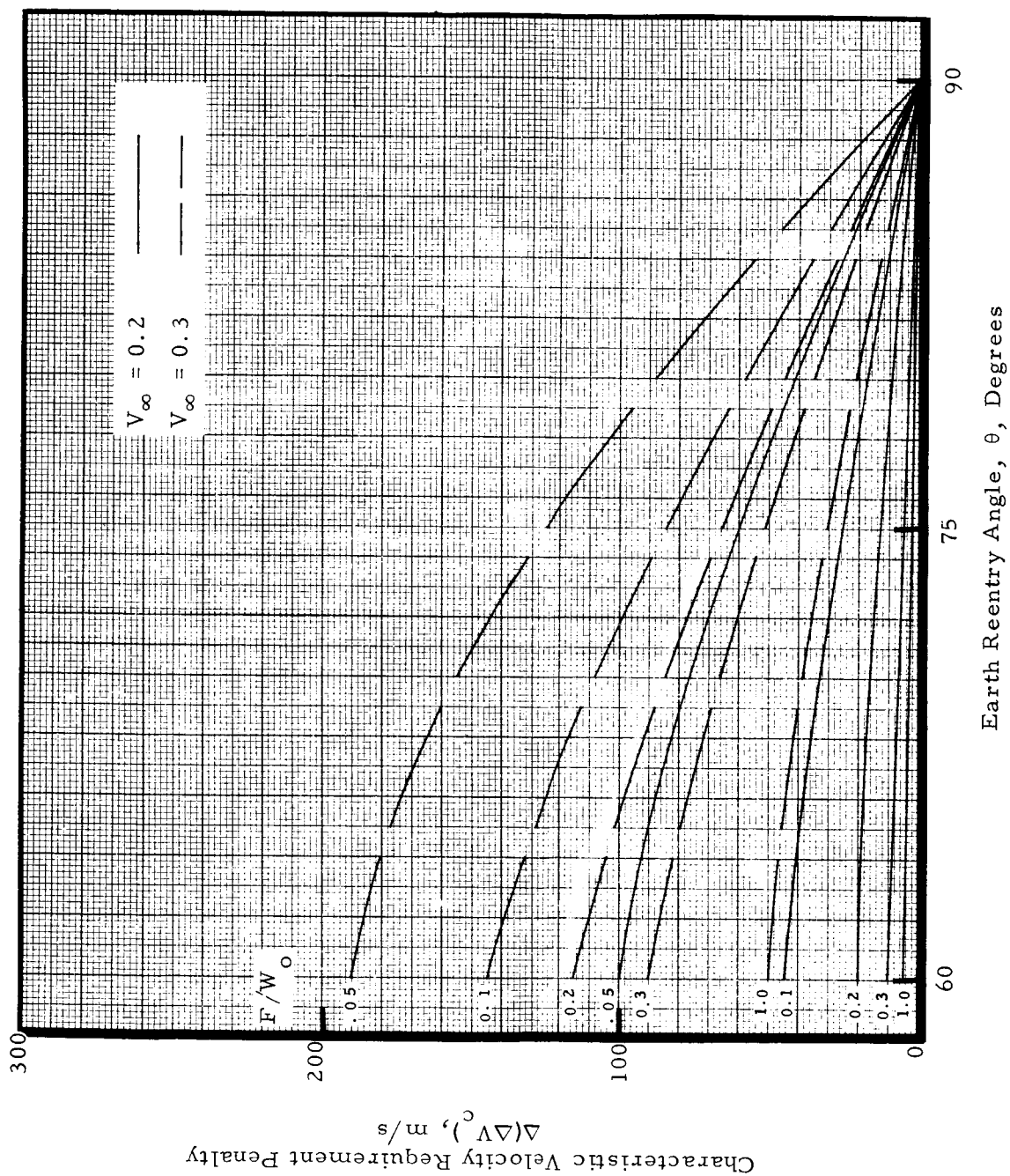


FIGURE 12a. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR  $\theta_{REF} = 90^\circ$   
 $I_{sp} = 330 \text{ sec}$   $(V)_{e \text{ max}} = 12000 \text{ m/s}$

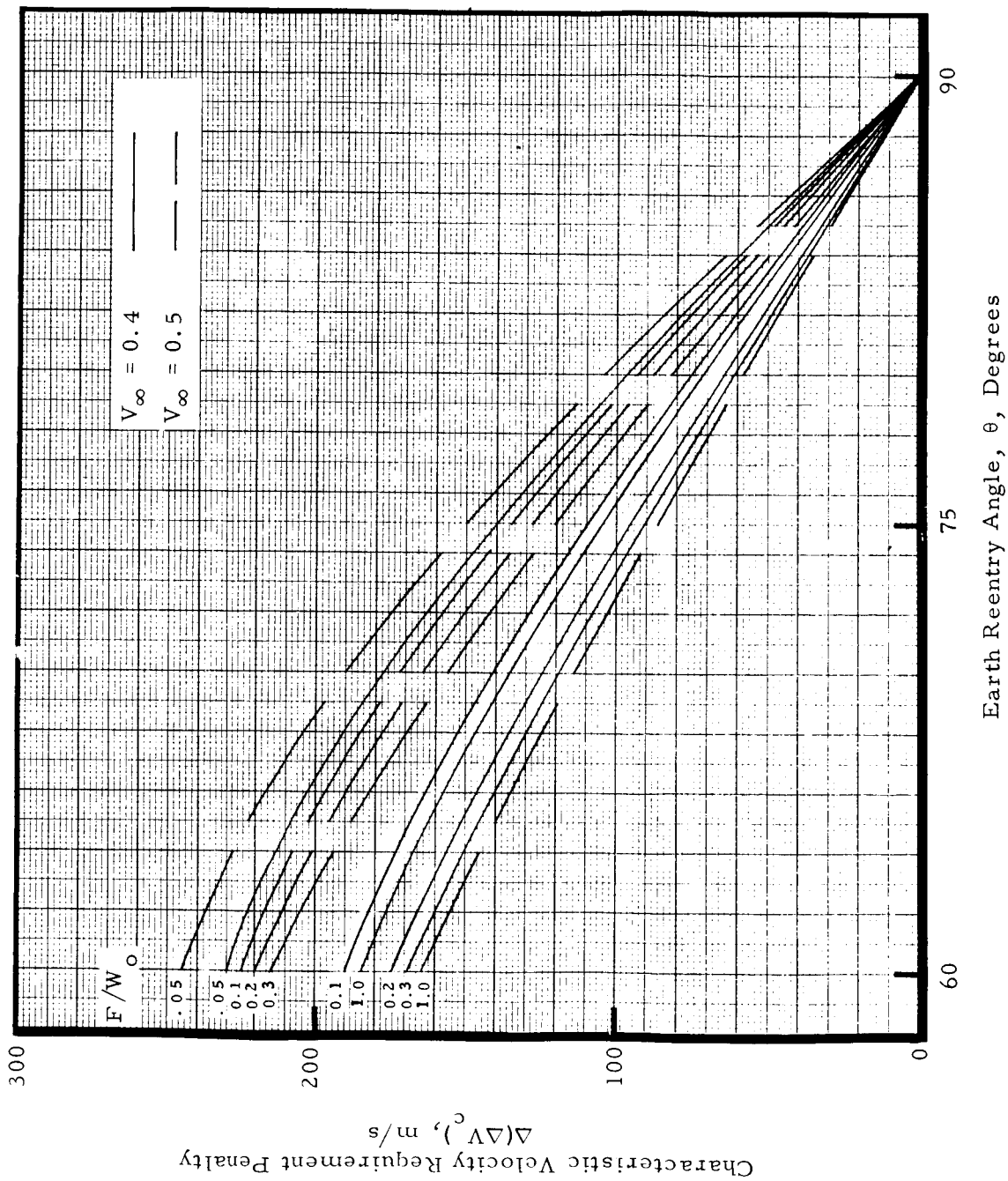


FIGURE 12b. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR  $\theta_{REF} = 90^\circ$

$I_{sp} = 330 \text{ sec}$

$(V_e)_{max} = 12000 \text{ m/s}$



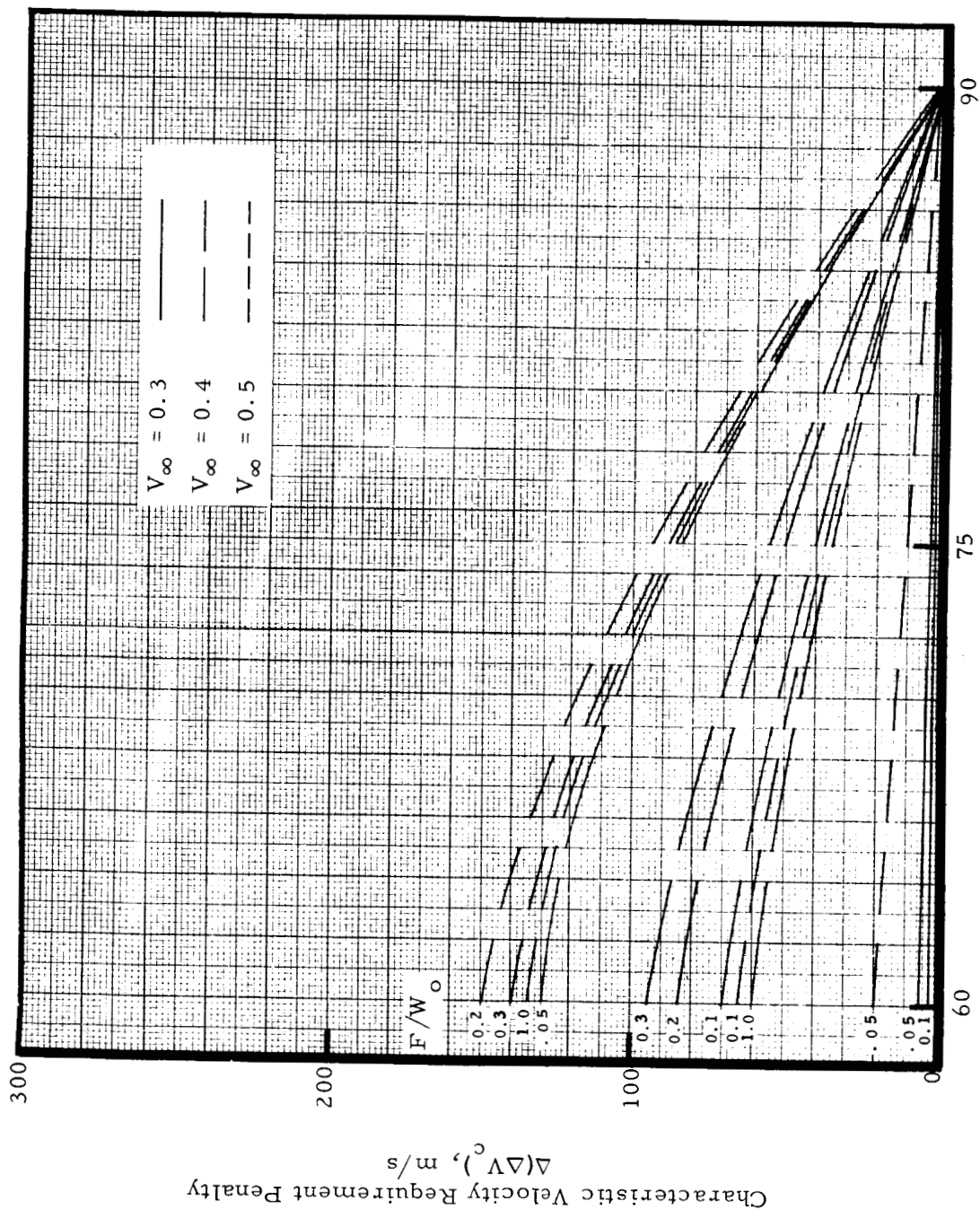


FIGURE 13. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR  $\theta_{REF} = 90^\circ$

$I_{sp} = 330 \text{ sec}$

$(V_e)_{max} = 14000 \text{ m/s}$

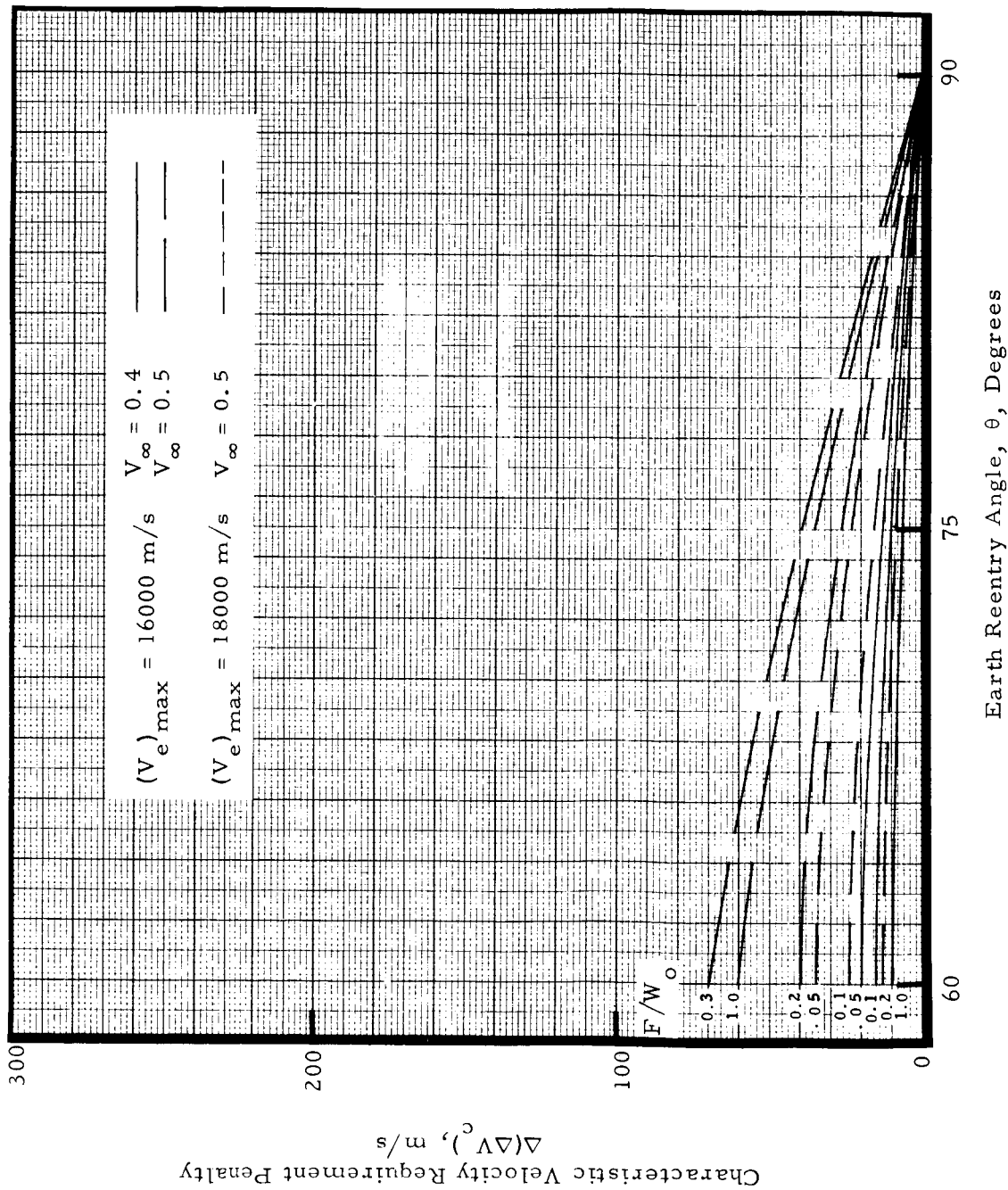


FIGURE 14. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR  $\theta_{REF} = 90^\circ$

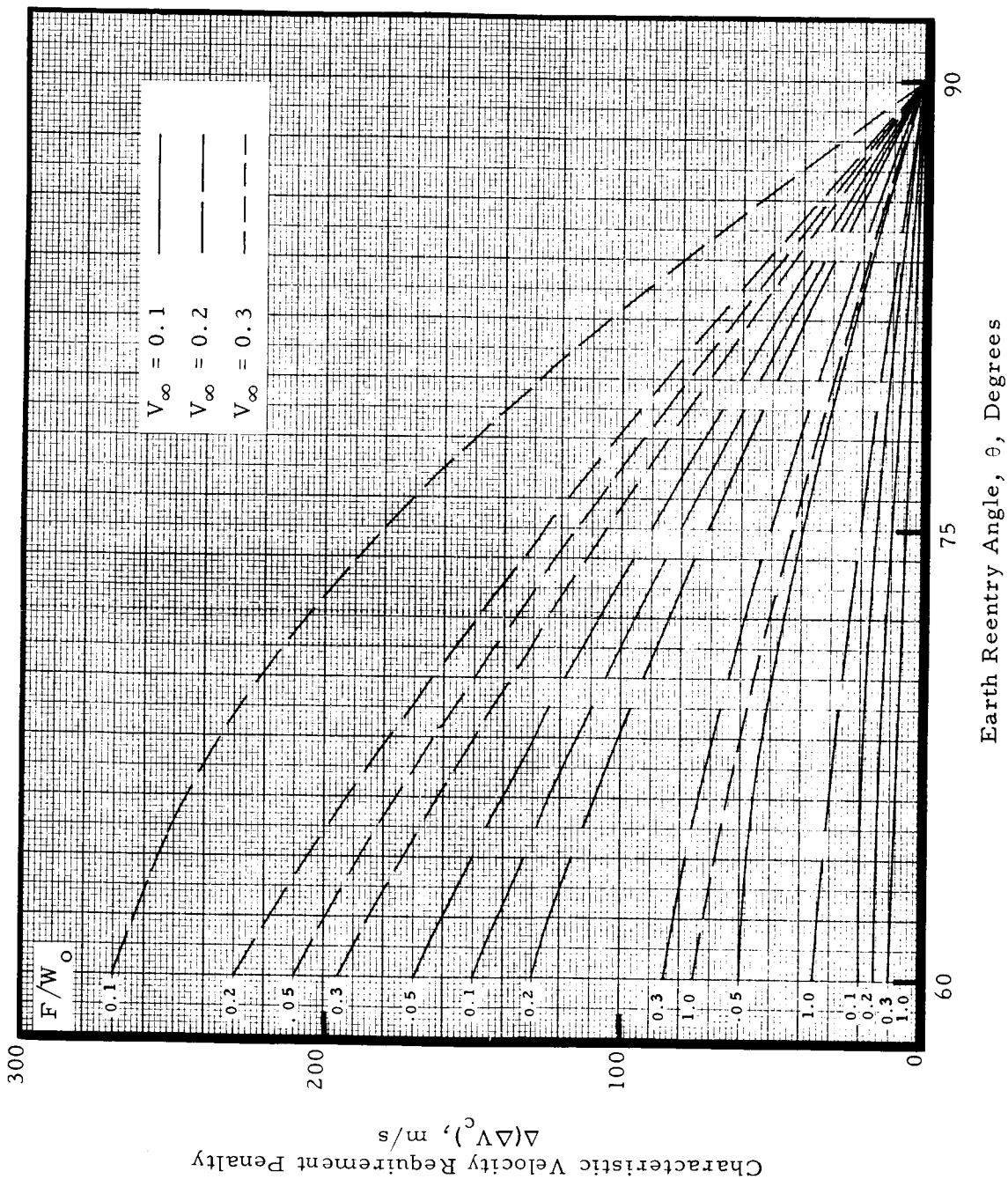


FIGURE 15a. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR  $\theta_{REF} = 90^\circ$

$I_{sp} = 430 \text{ sec}$

$(V_e)_{max} = 11030 \text{ m/s}$

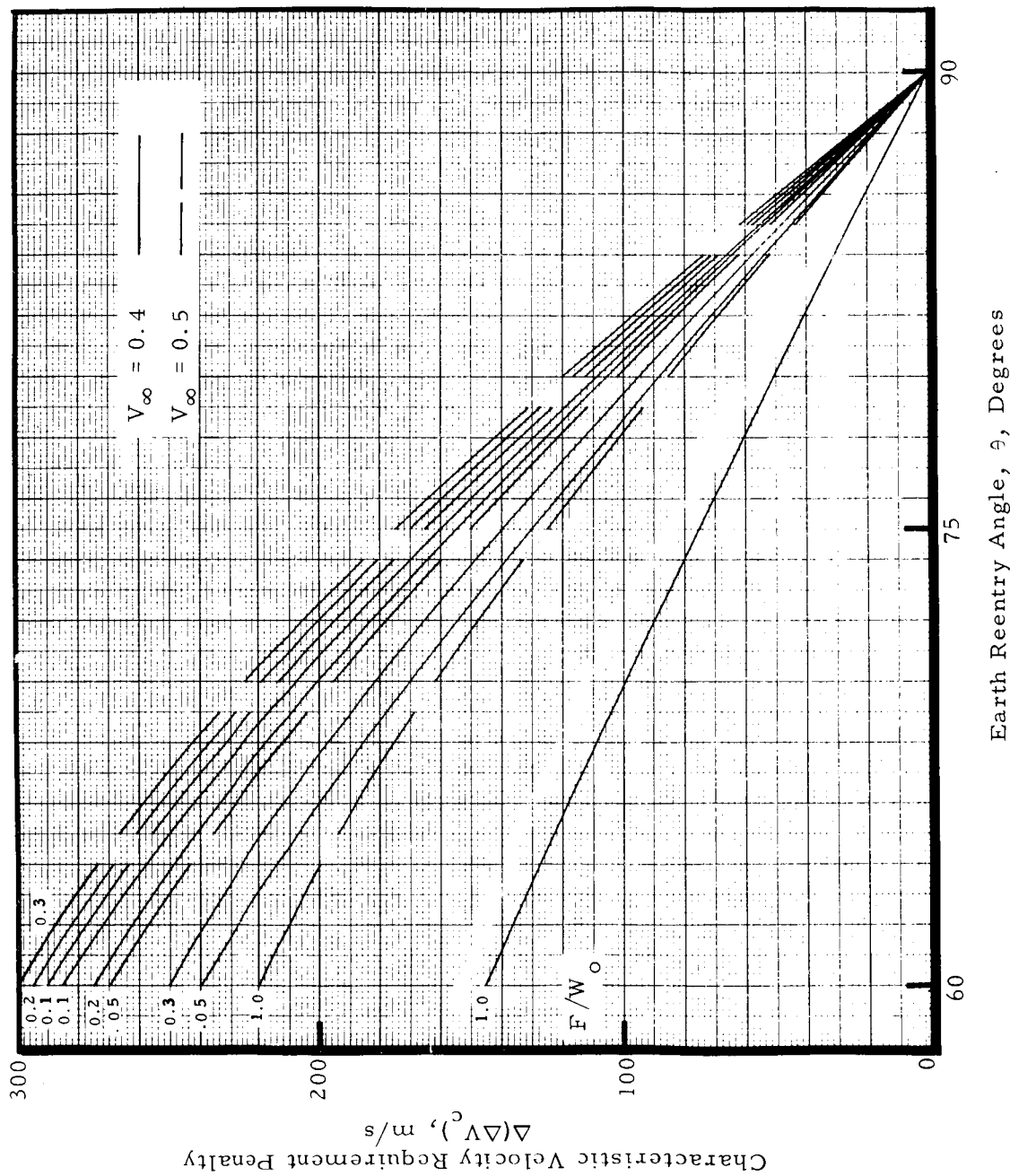


FIGURE 15b. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR  $\theta_{REF} = 90^\circ$

$I_{sp} = 430 \text{ sec}$

$(V_e)_{max} = 11030 \text{ m/s}$

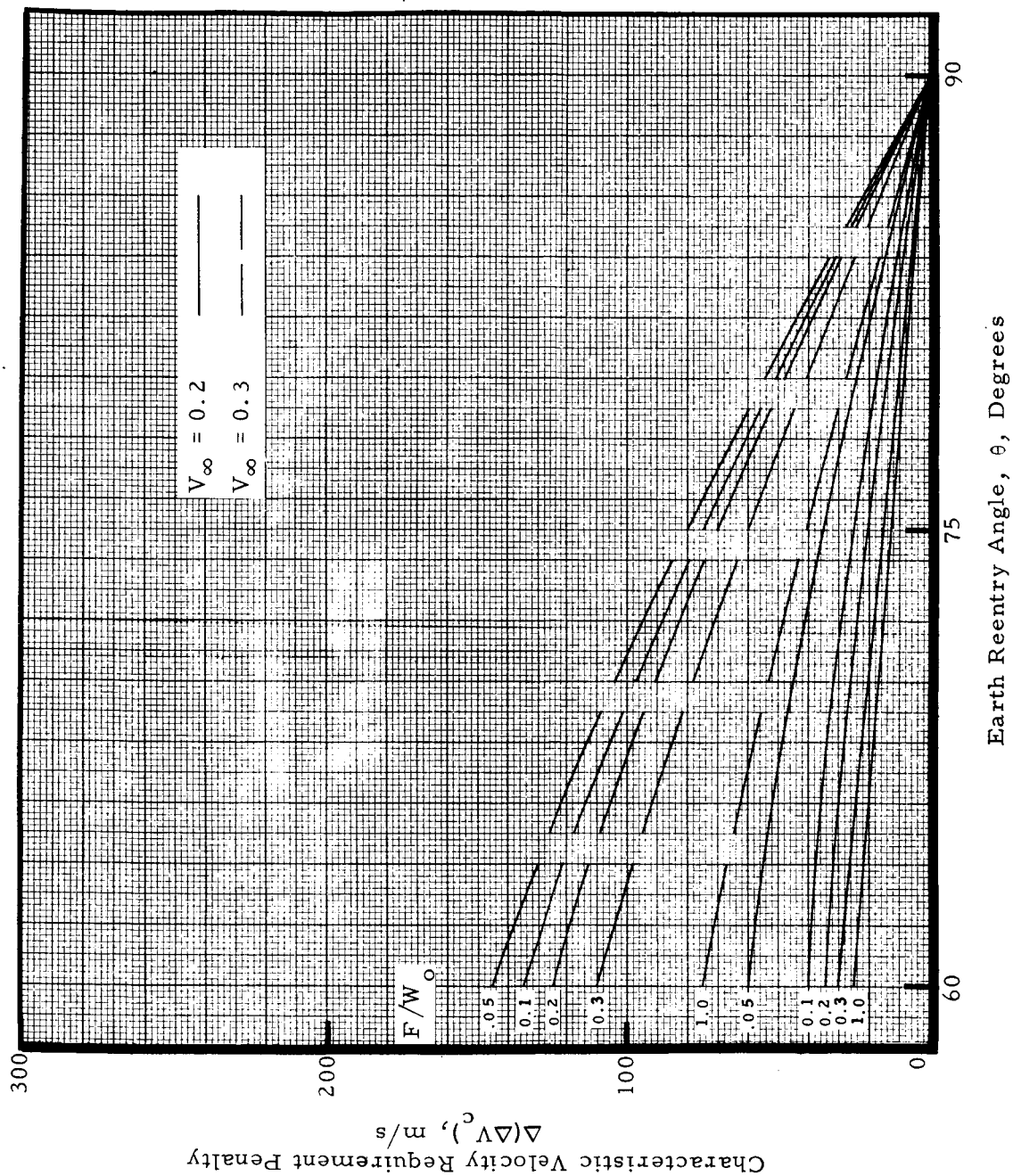


FIGURE 16a. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR  $\theta_{REF} = 90^\circ$   
 $I_{sp} = 430 \text{ sec}$   $(V_e)_{max} = 12000 \text{ m/s}$

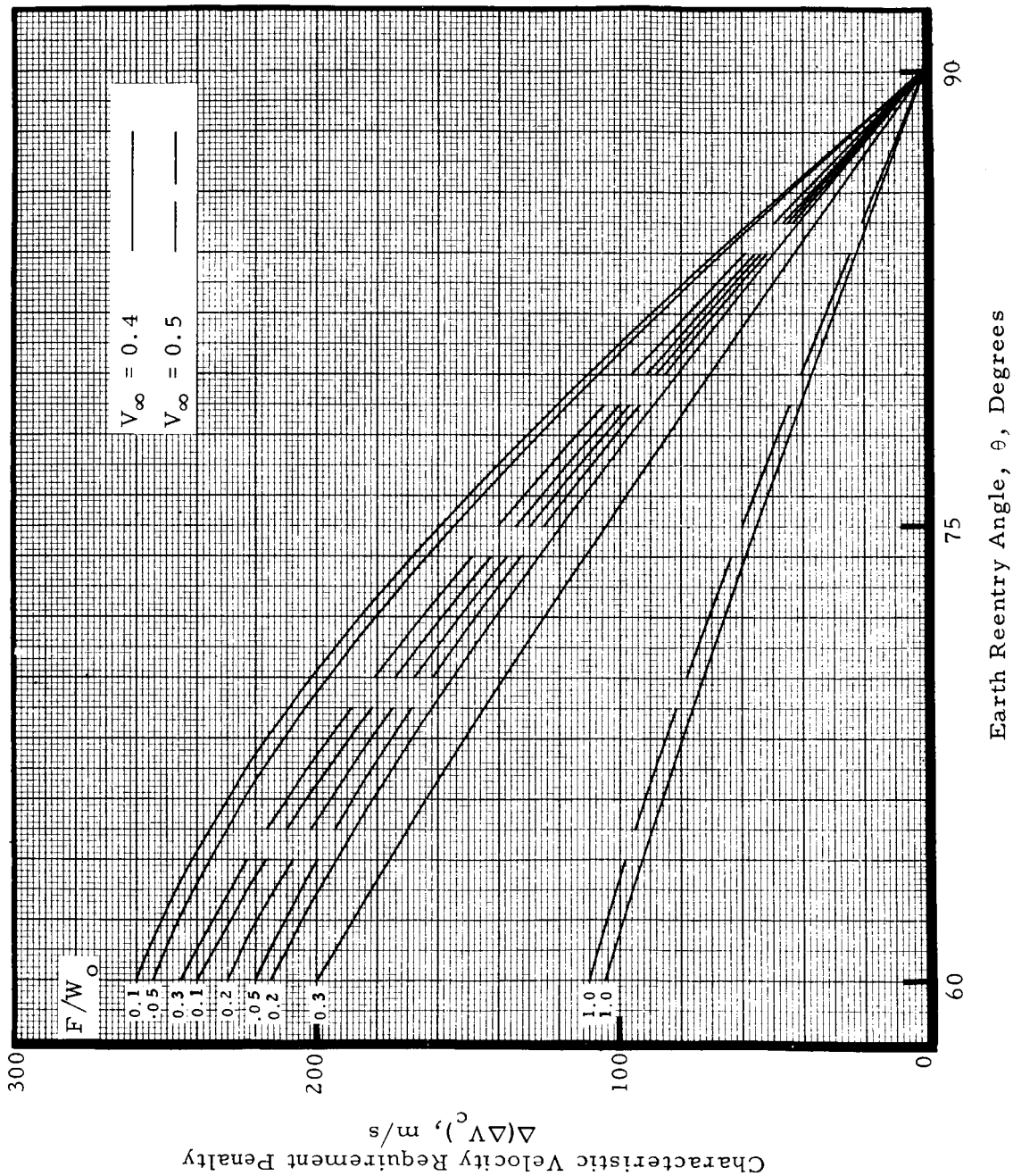


FIGURE 16b. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR  $\theta_{REF} = 90^\circ$

$I_{sp} = 430 \text{ sec}$

$(V)_{e \max} = 12000 \text{ m/s}$

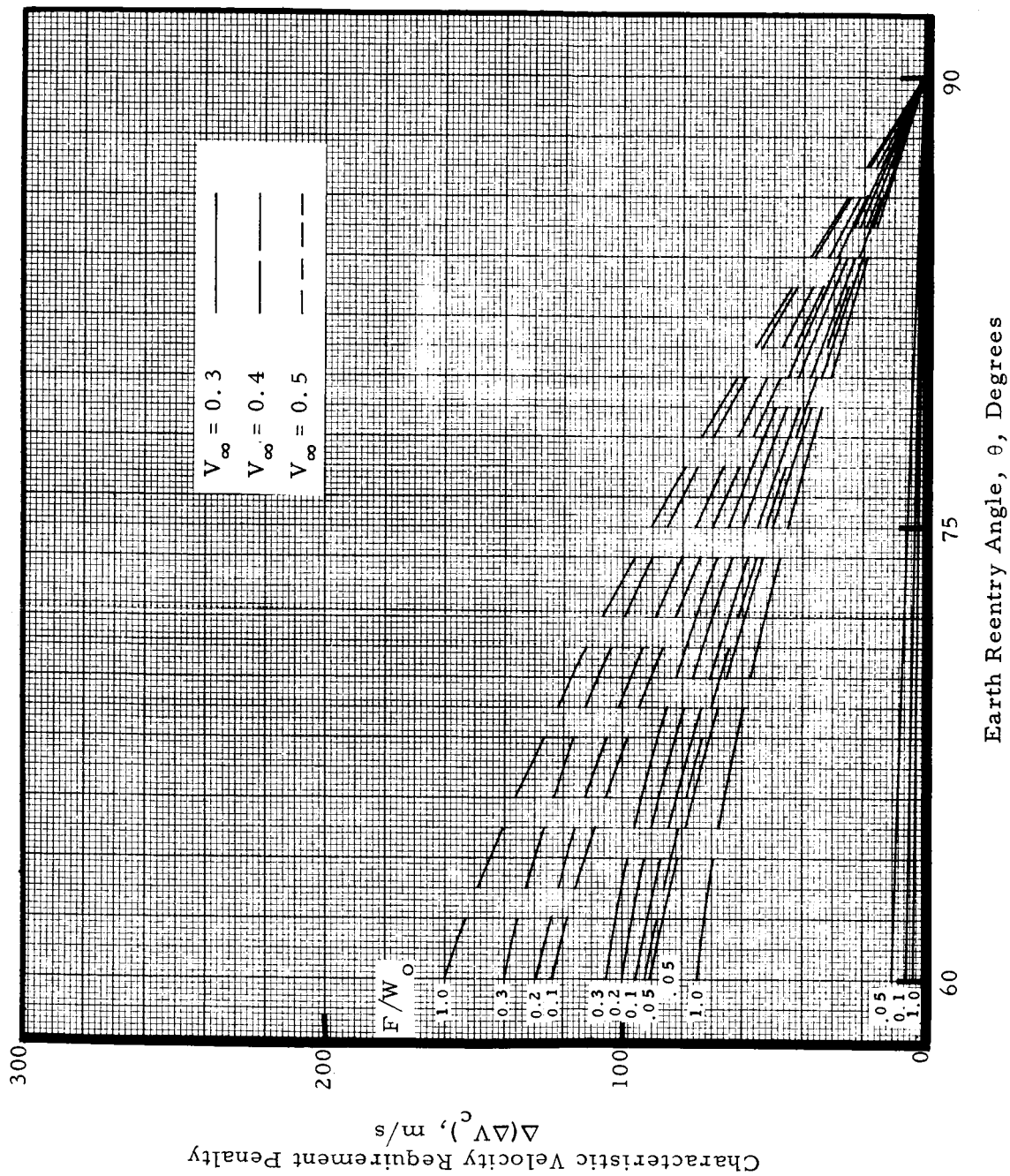


FIGURE 17 CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR  $\theta_{REF} = 90^\circ$

$$I_{sp} = 430 \text{ sec}$$

$$(V_e)_{max} = 14000 \text{ m/s}$$

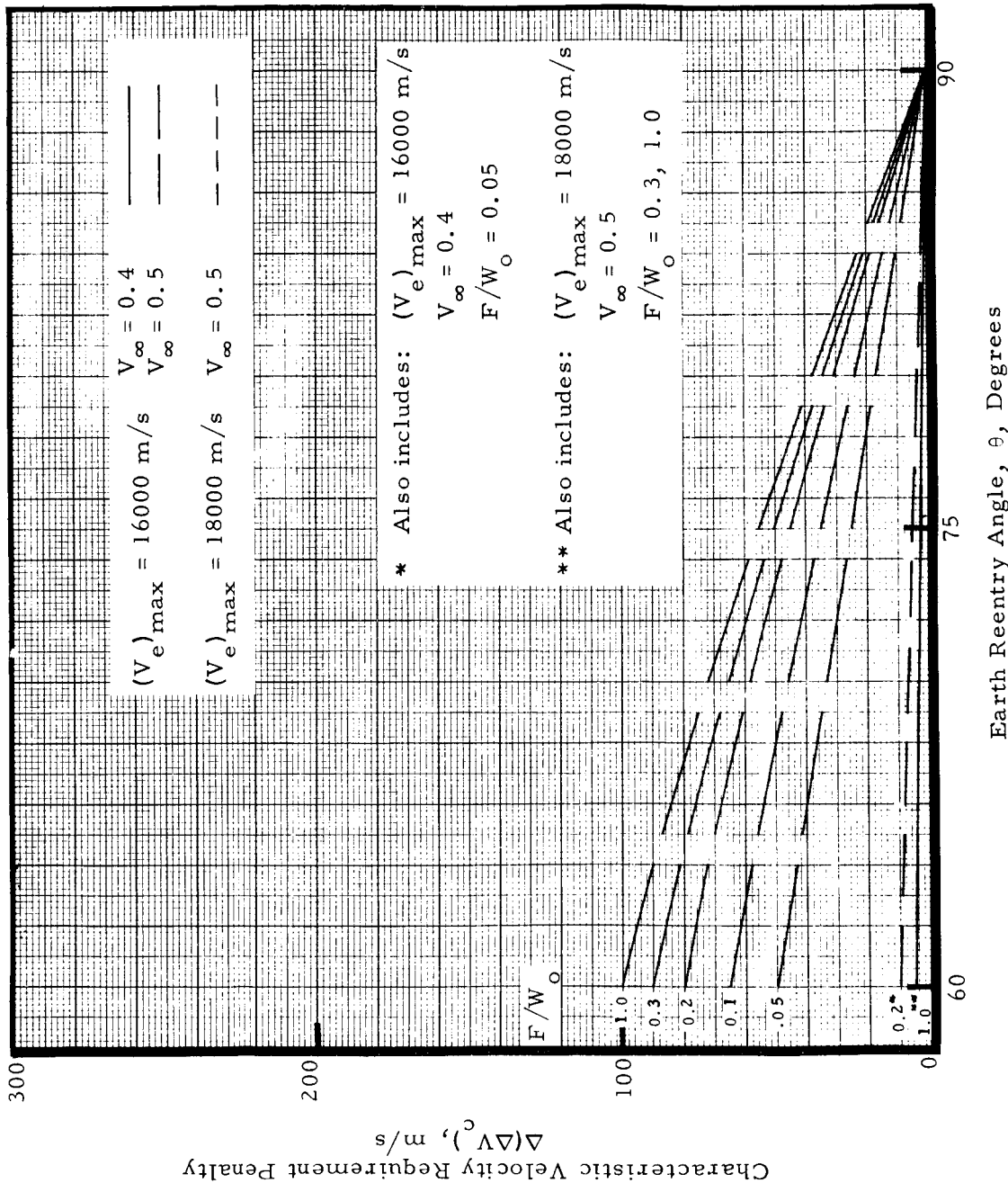


FIGURE 18. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR  $\theta_{\text{REF}} = 90^\circ$   
 $I_{\text{sp}} = 430 \text{ sec}$   
 $(V_e)_{\max} = 16000\text{-}18000 \text{ m/s}$



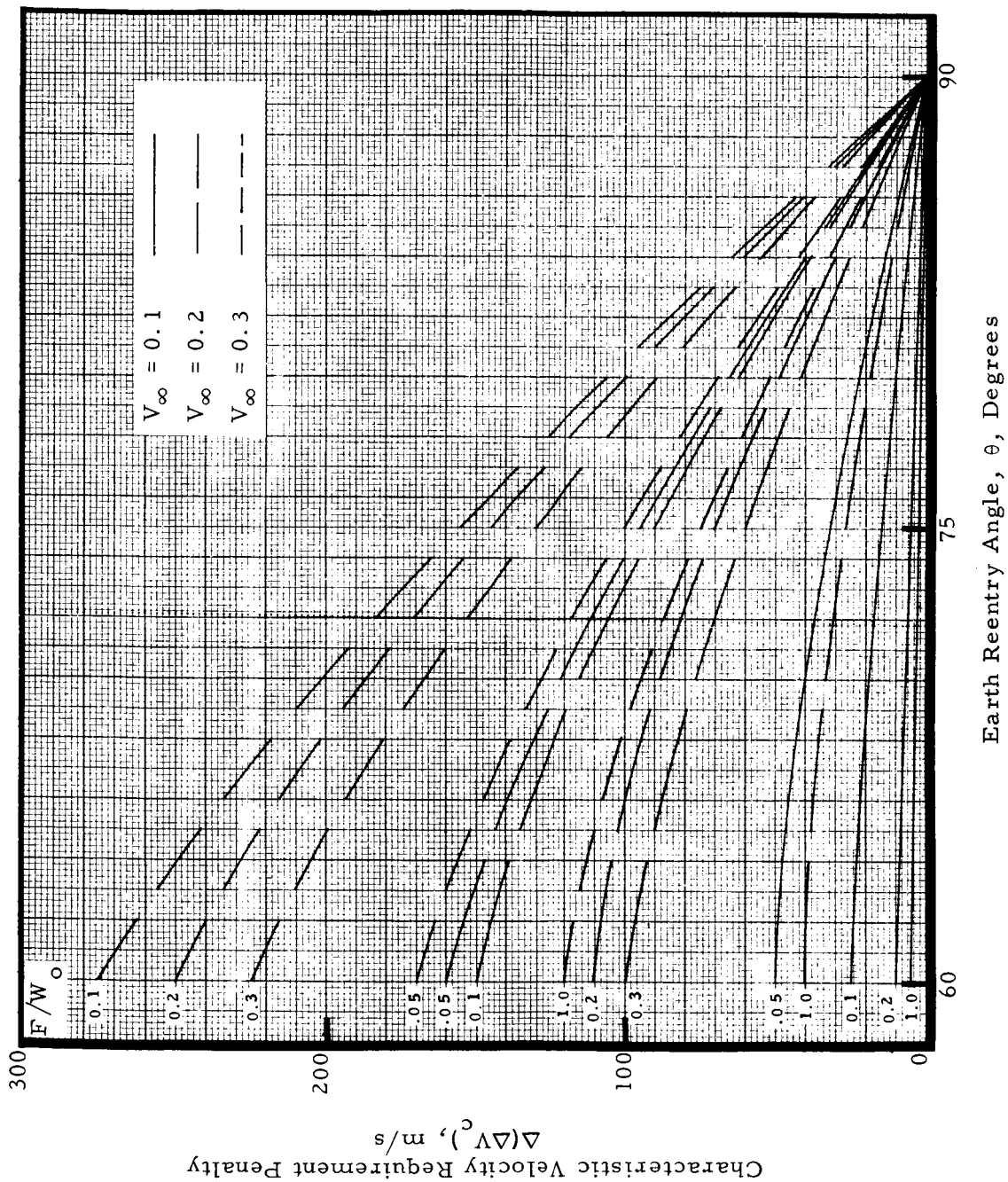


FIGURE 19a. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR  $\theta_{REF} = 90^\circ$   
 $I_{sp} = 800 \text{ sec}$   $(V_e)_{max} = 11030 \text{ m/s}$

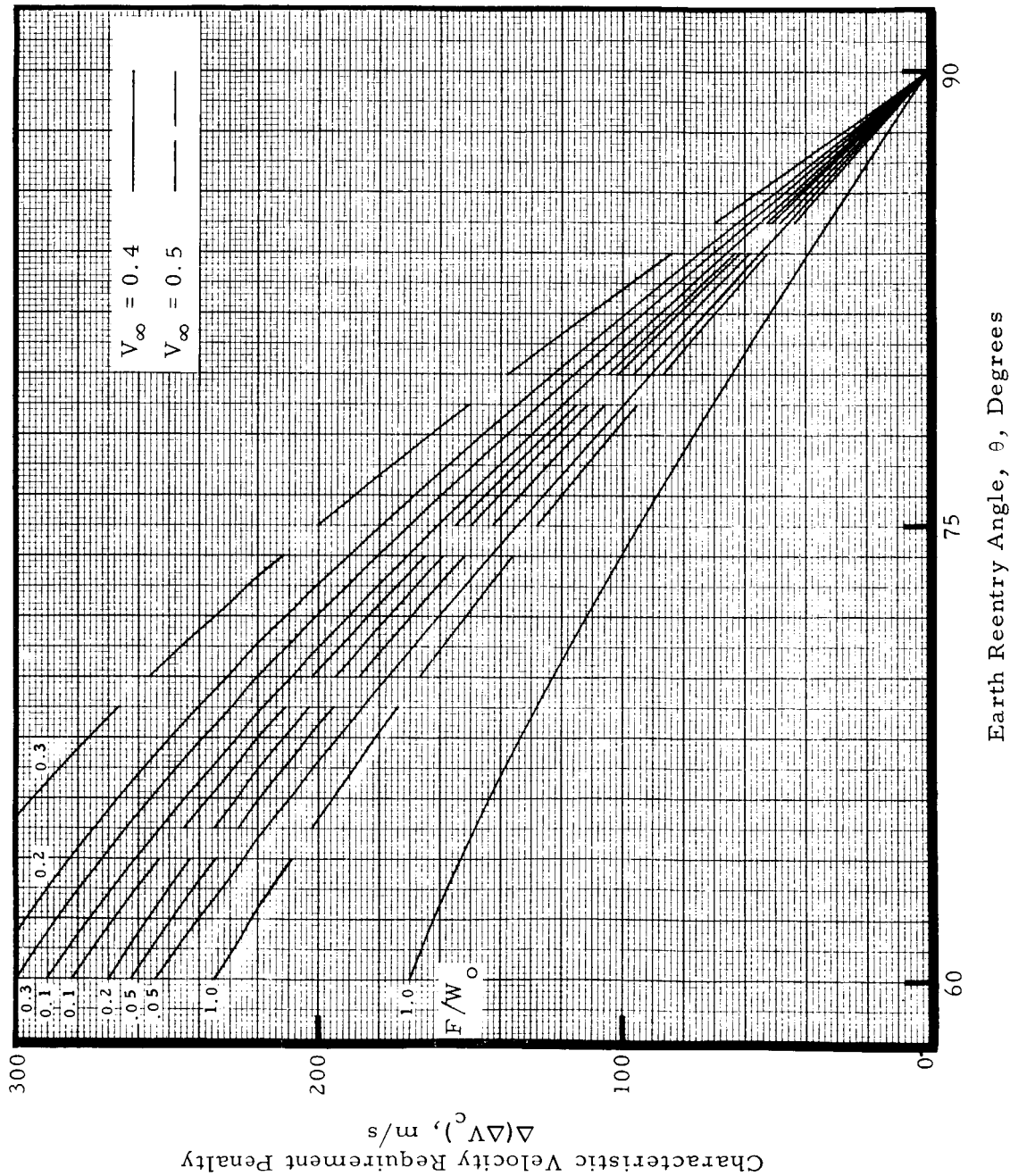


FIGURE 19b. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR  $\theta_{REF} = 90^\circ$

$I_{sp} = 800$  sec

$(V_e)_{max} = 11030$  m/s

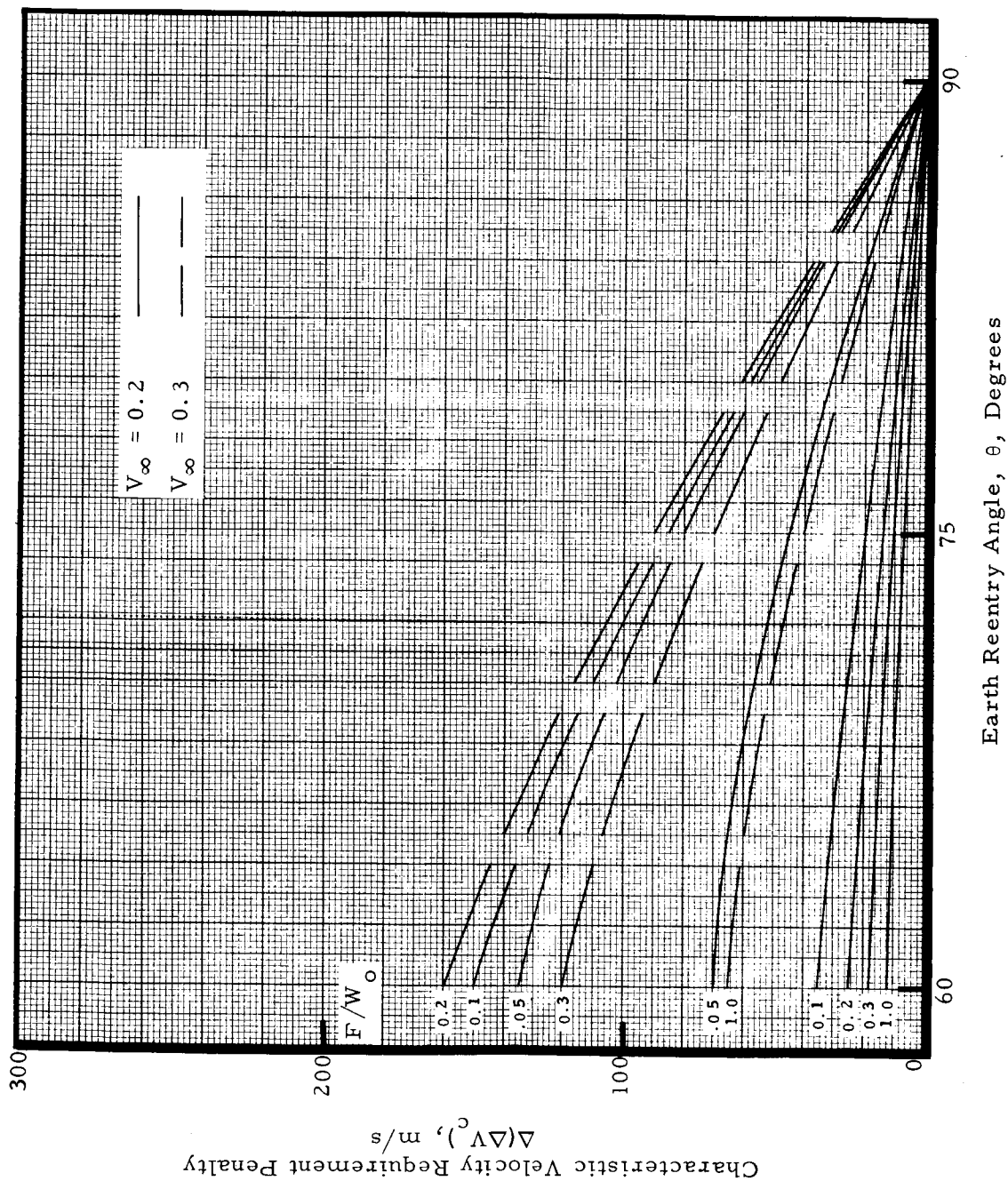


FIGURE 20a. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR  $\theta_{REF} = 90^\circ$   
 $I_{sp} = 800$  sec  $(V_e)_{max} = 12000$  m/s

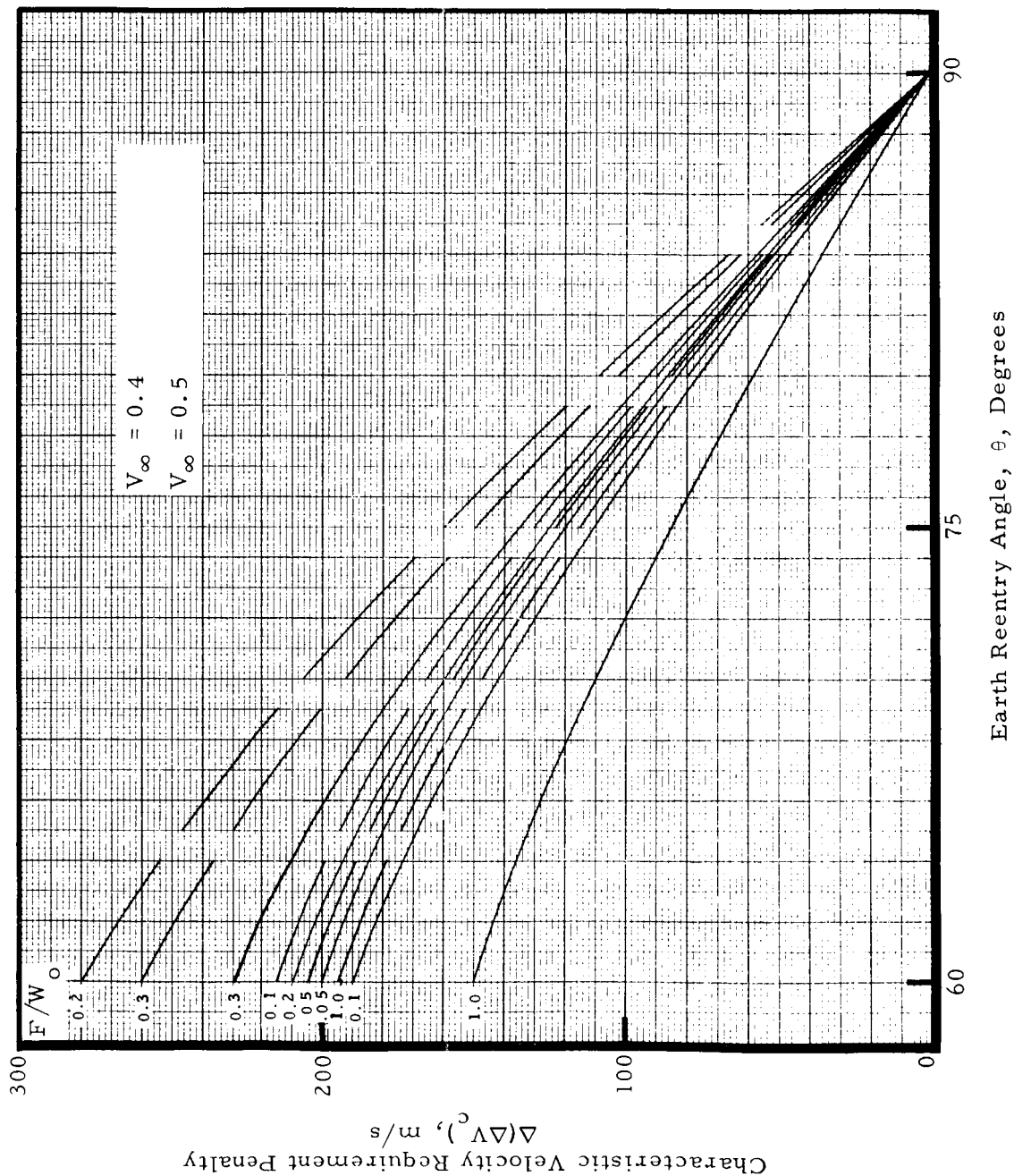


FIGURE 20b. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR  $\theta_{REF} = 90^\circ$

$I_{sp} = 800$  sec

$(V_e)_{max} = 12000$  m/s

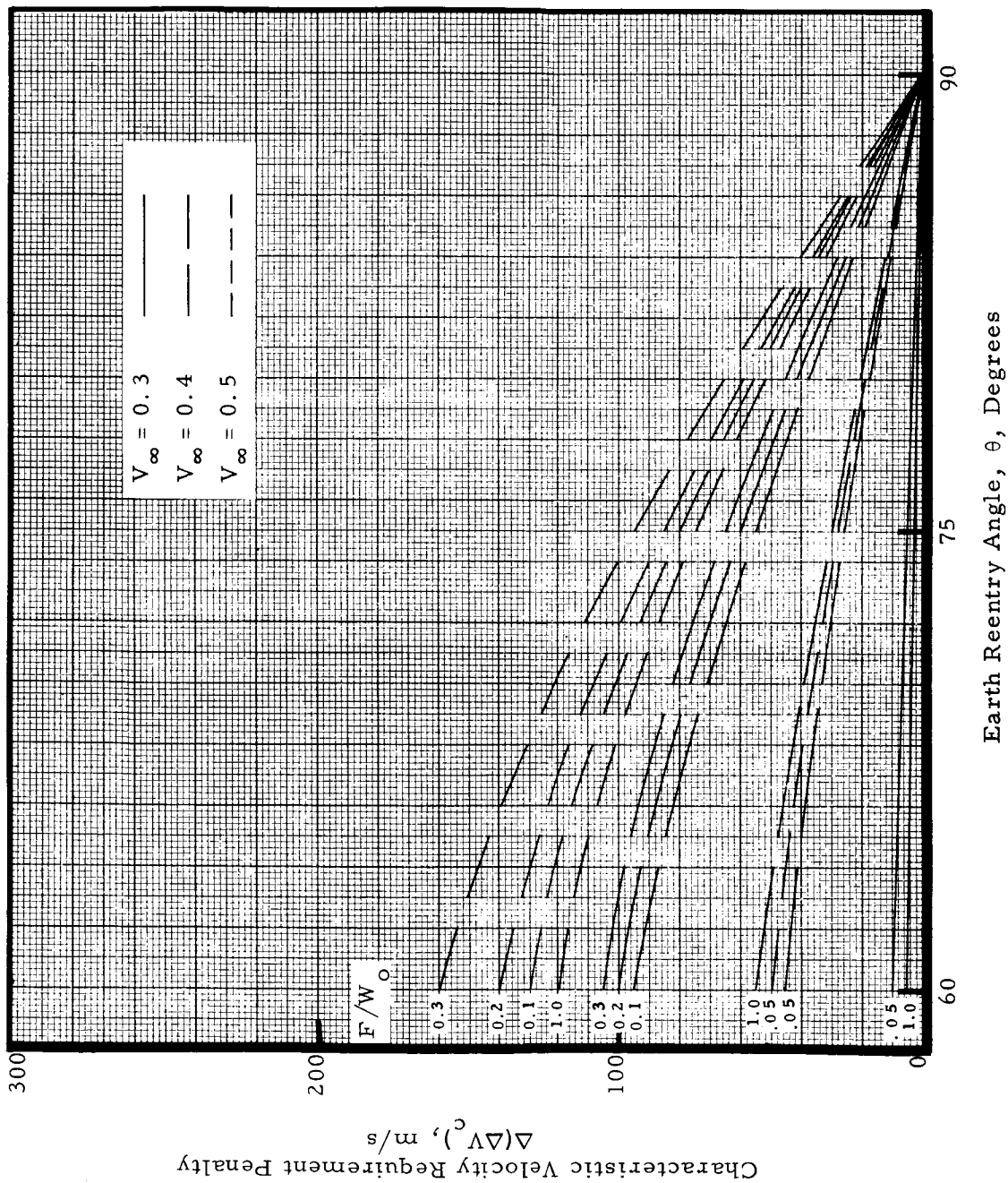


FIGURE 21. CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR  $\theta_{REF} = 90^\circ$   
 $I_{sp} = 800 \text{ sec}$   $(V)_{e \max} = 14000 \text{ m/s}$

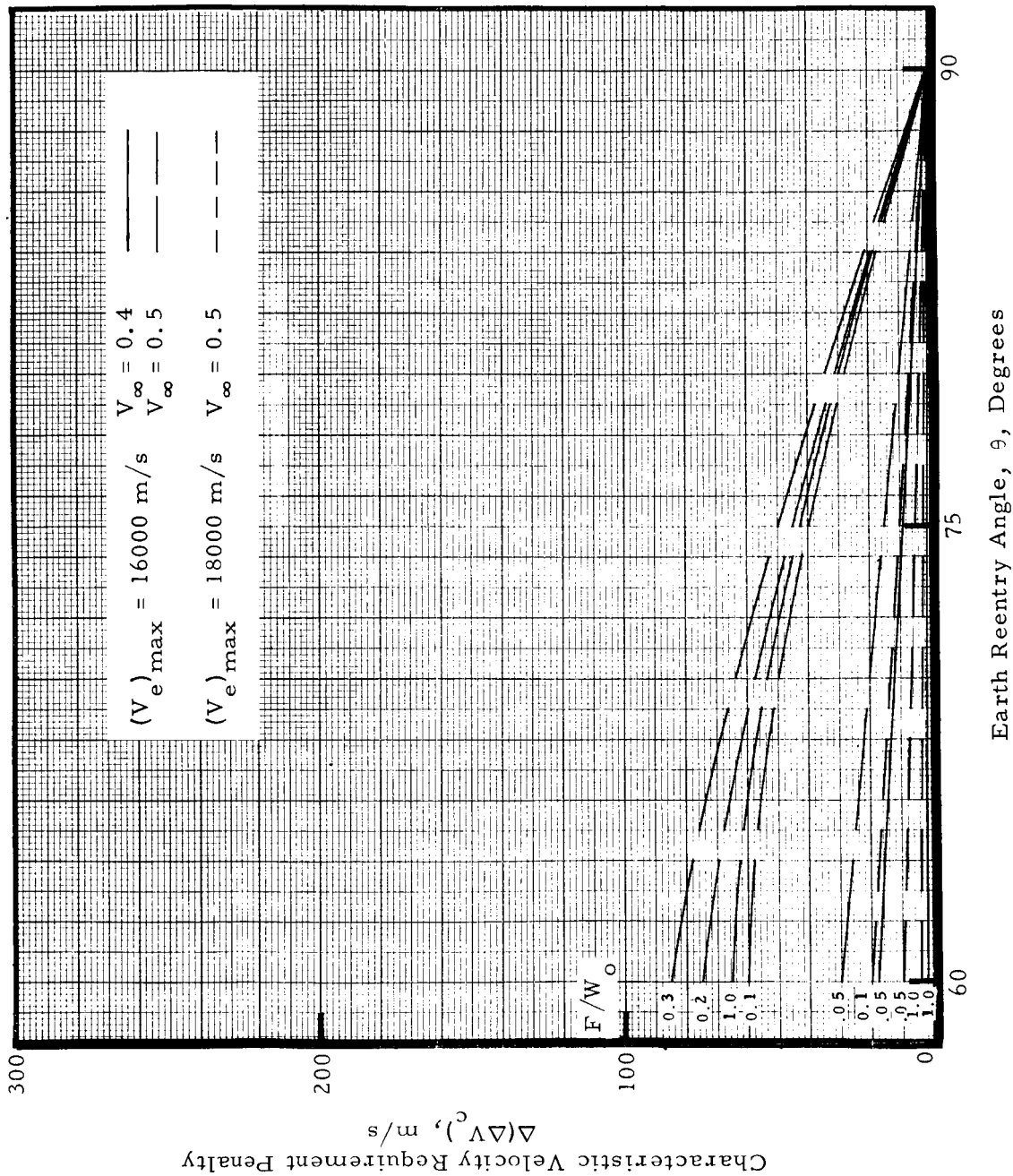


FIGURE 22 CHARACTERISTIC VELOCITY REQUIREMENT PENALTY FOR  $\theta_{REF} = 90^\circ$

$I_{sp} = 800 \text{ sec}$   $(V_e)_{\max} = 16000-18000 \text{ m/s}$

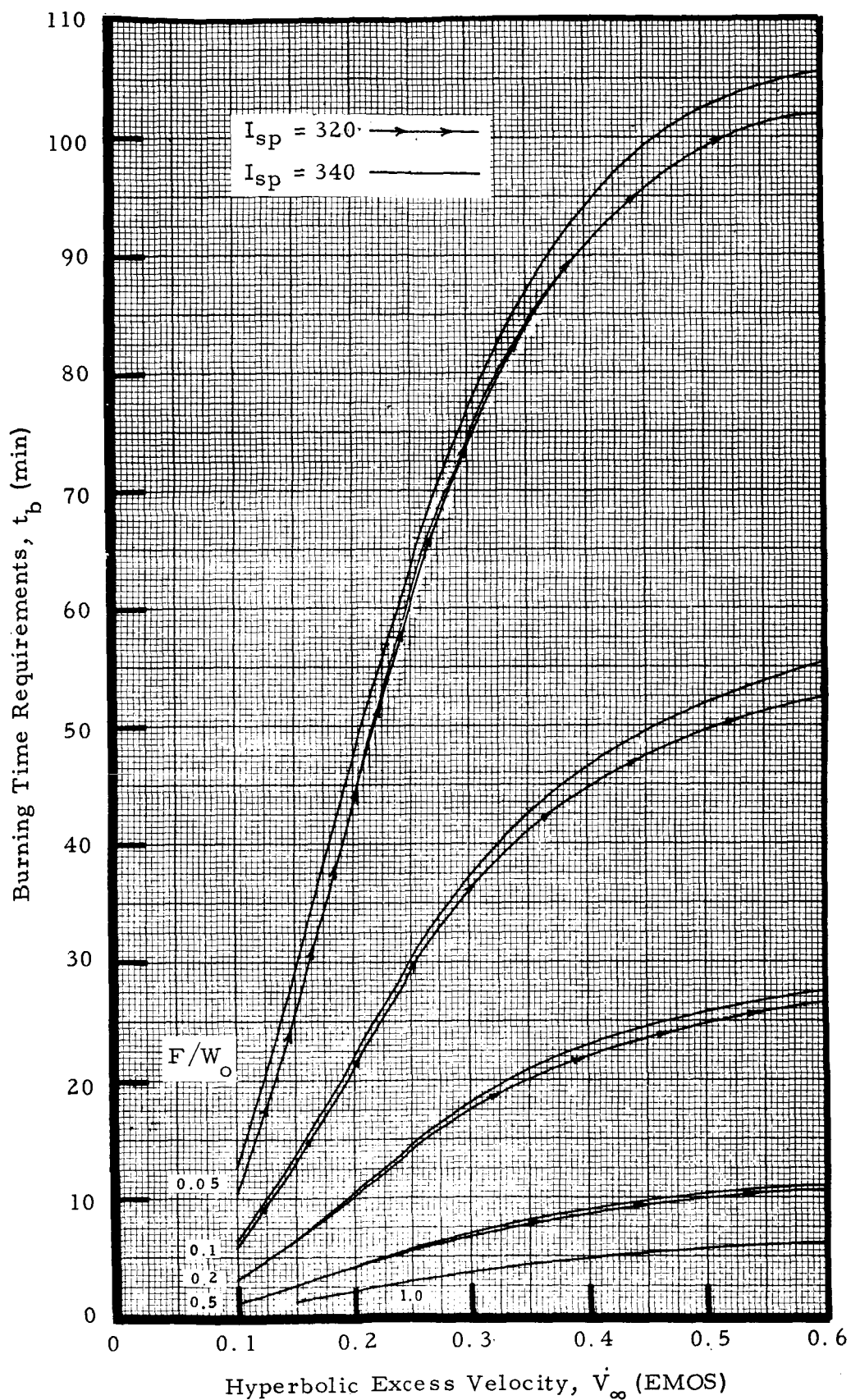


FIGURE 23a. BURNING TIME REQUIREMENTS FOR  
 $I_{sp} = 320$  s AND  $340$  s,  $(V_e)_{max} = 11030$  m/s



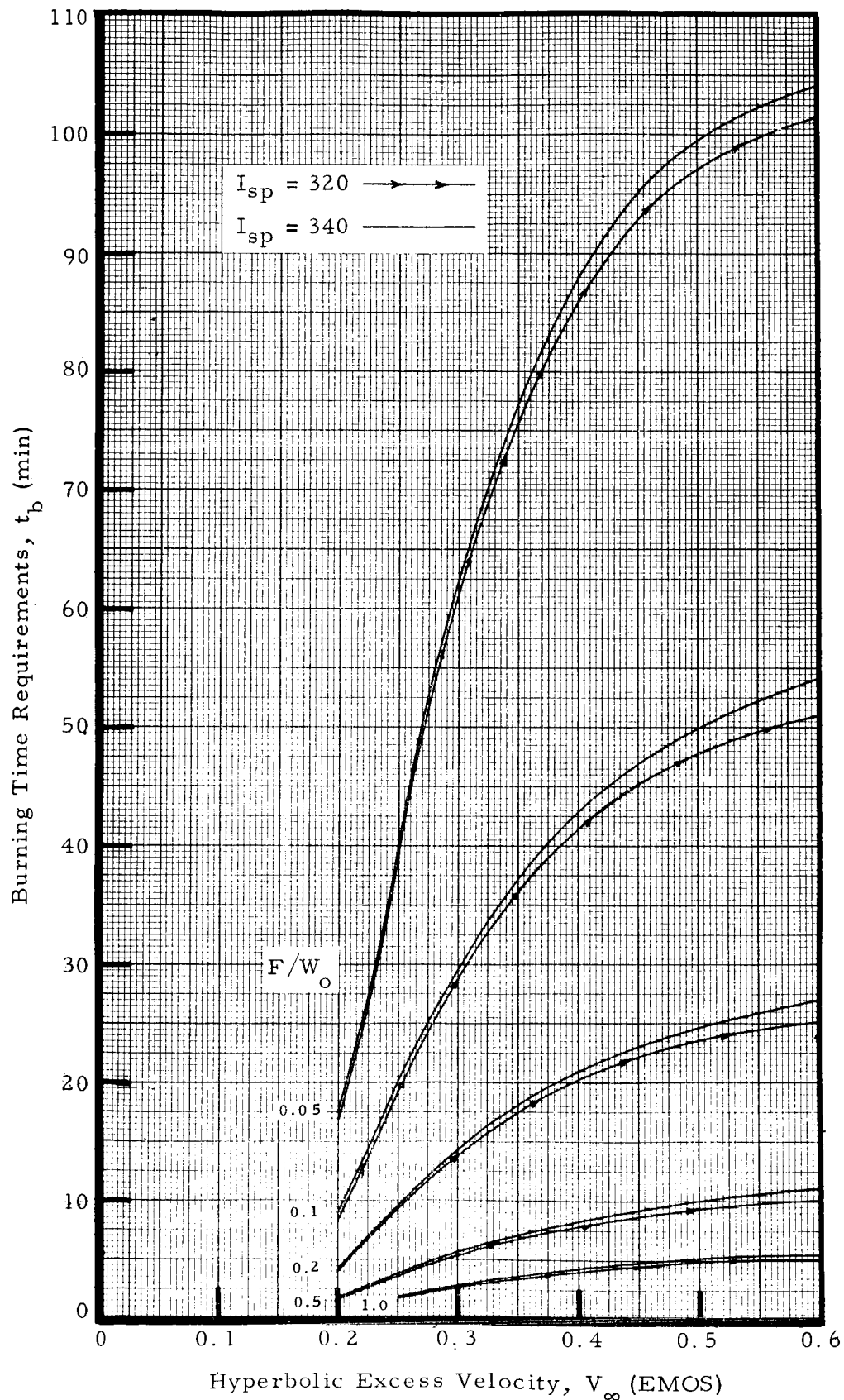


FIGURE 23b. BURNING TIME REQUIREMENTS FOR  
 $I_{sp} = 320$  s AND  $340$  s,  $(V_e)_{max} = 12000$  m/s

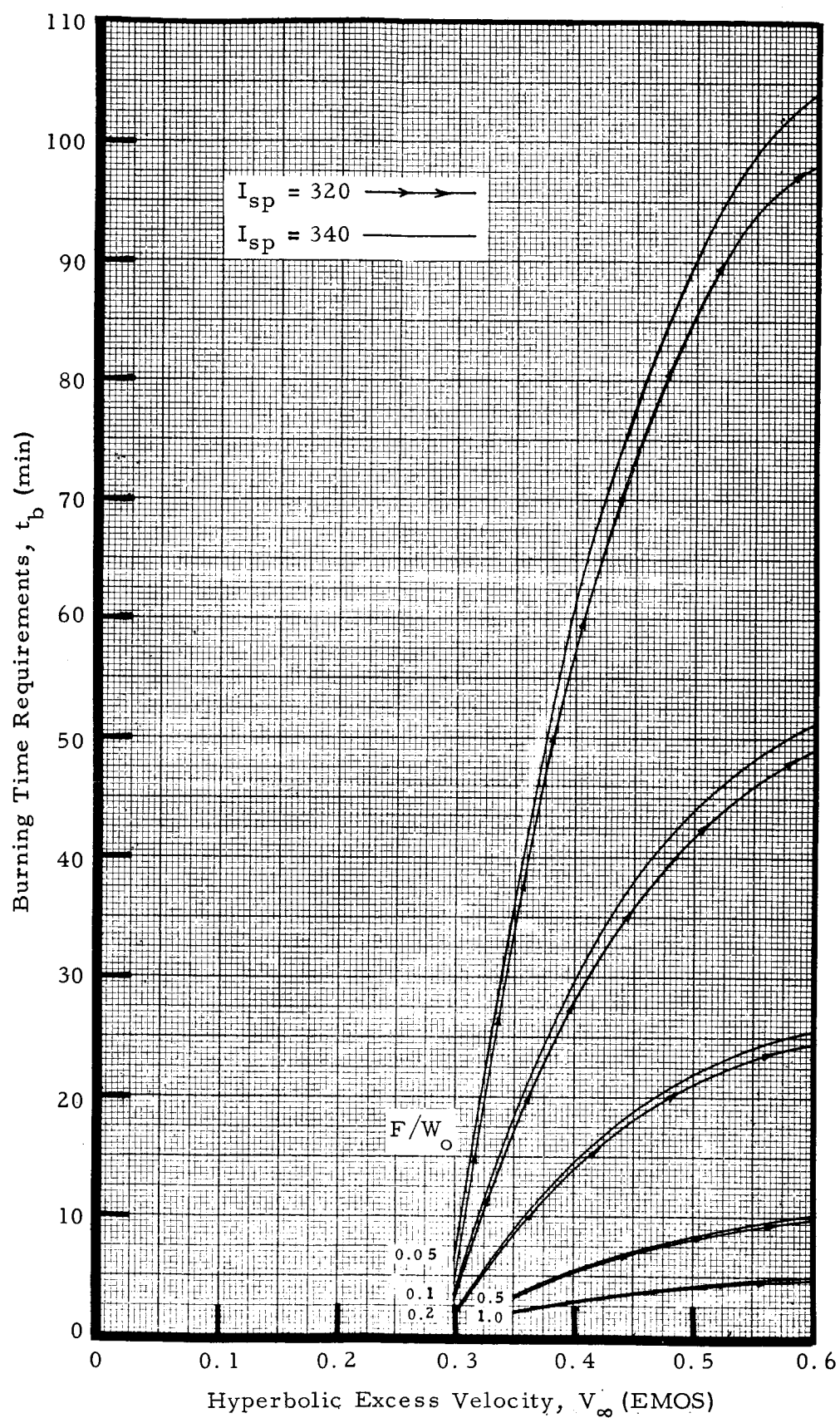


FIGURE 23c. BURNING TIME REQUIREMENTS FOR  
 $I_{sp} = 320$  s AND  $340$  s,  $(V_e)_{max} = 14000$  m/s

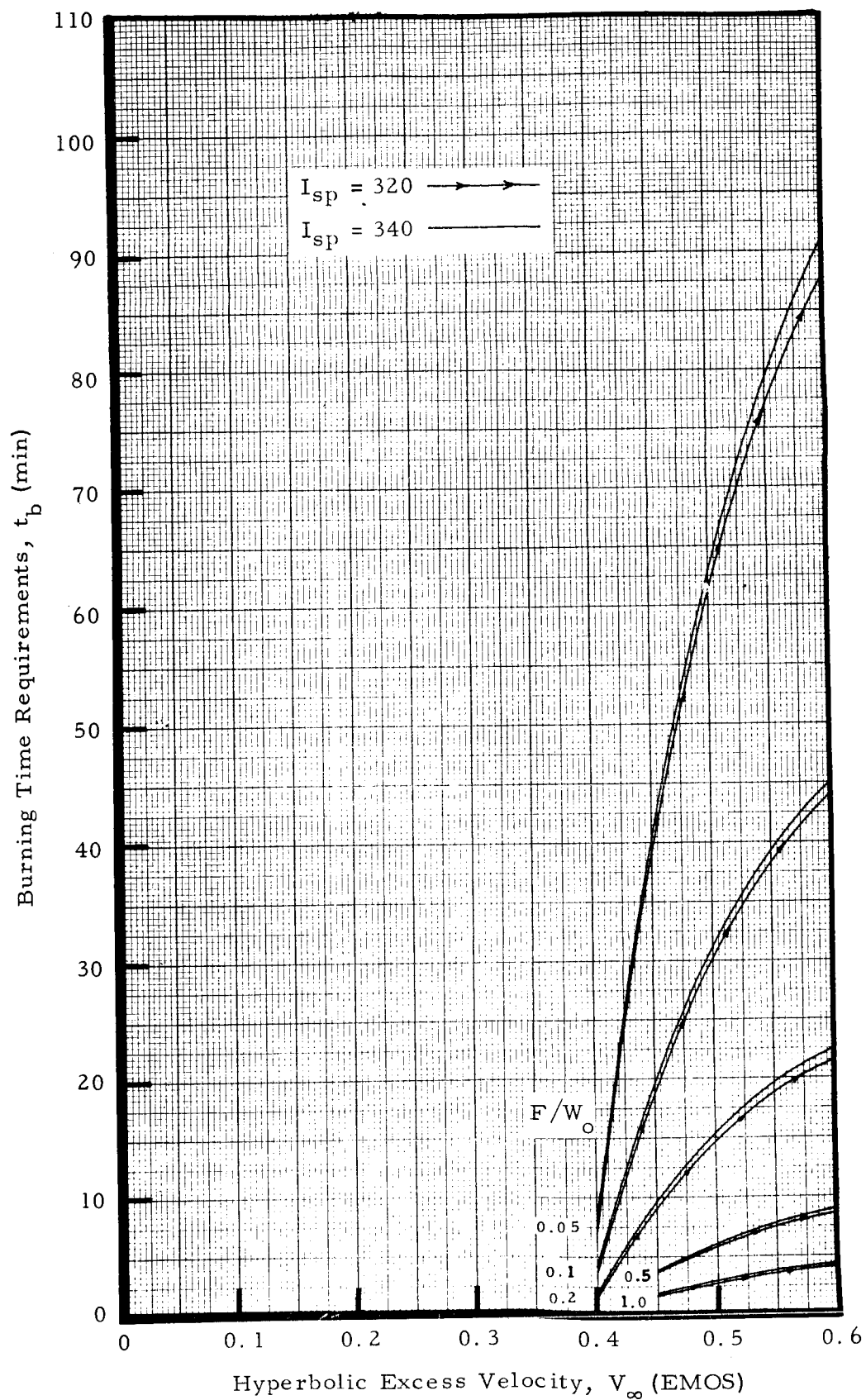


FIGURE 23d. BURNING TIME REQUIREMENTS FOR  
 $I_{sp} = 320$  s AND  $340$  s,  $(V_e)_{max} = 16000$  m/s

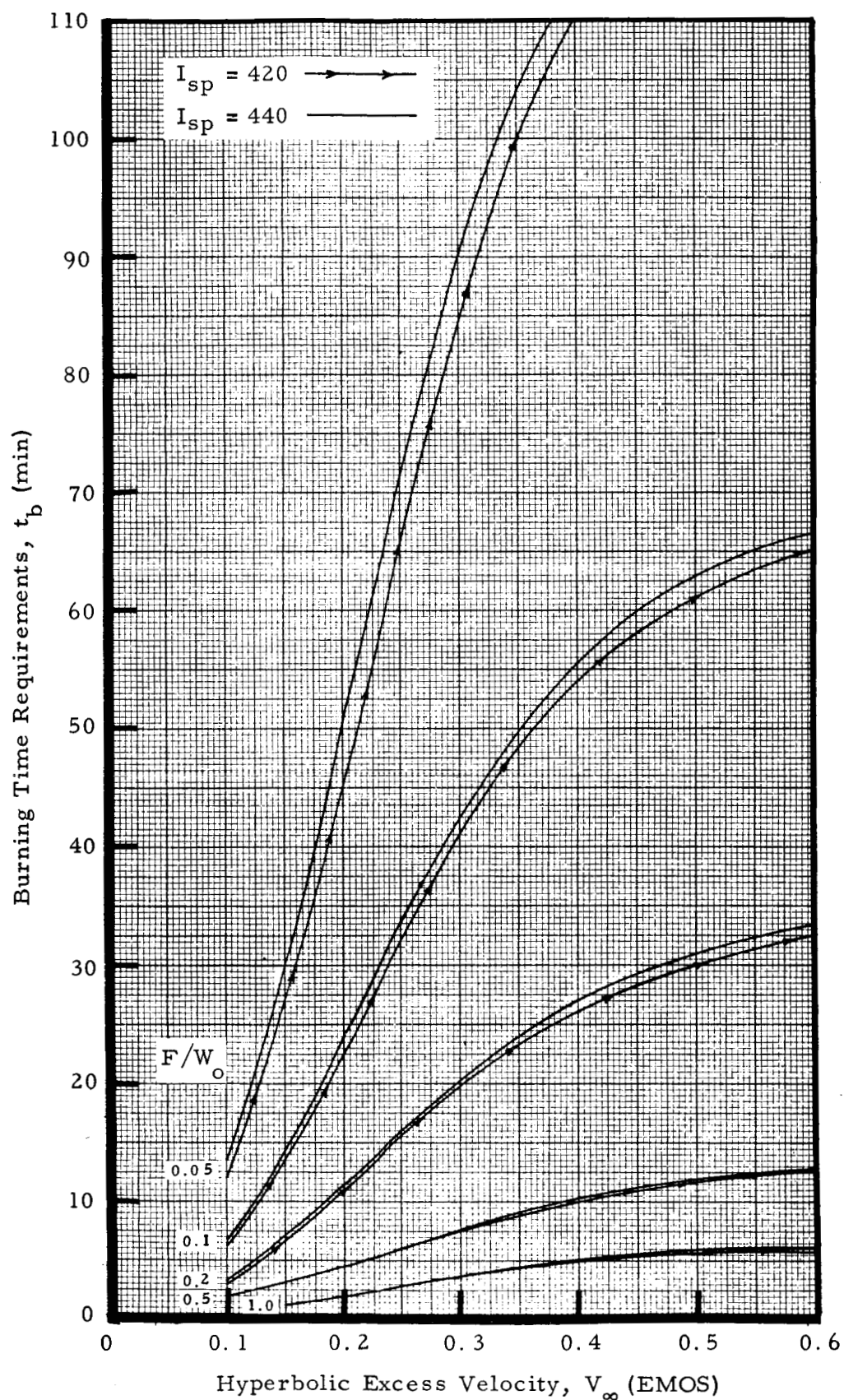


FIGURE 24a. BURNING TIME REQUIREMENTS FOR  
 $I_{sp} = 420$  s AND  $440$  s,  $(V_e)_{max} = 11030$  m/s

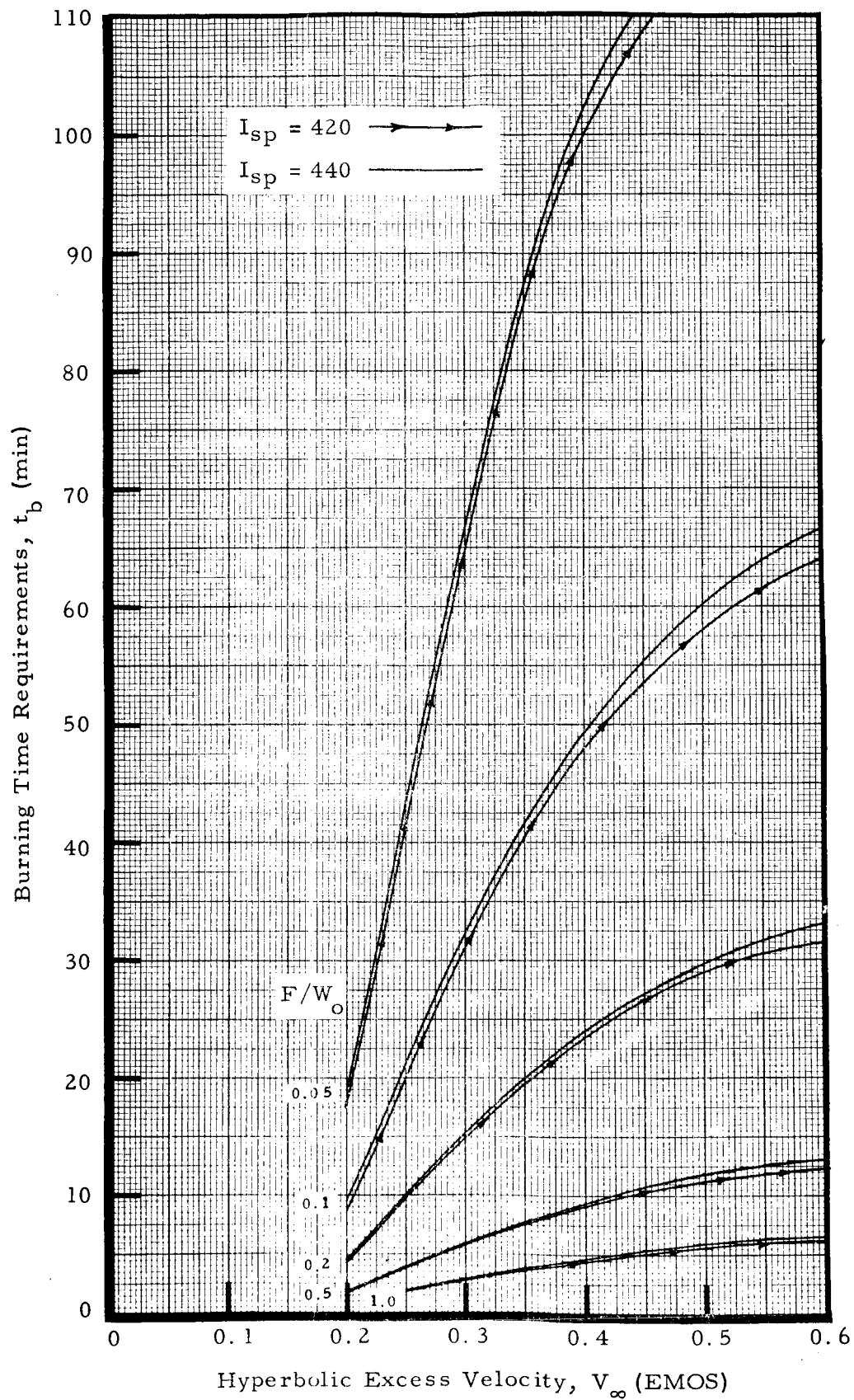


FIGURE 24b. BURNING TIME REQUIREMENTS FOR  
 $I_{sp} = 420$  s AND  $440$  s,  $(V_e)_{max} = 12000$  m/s

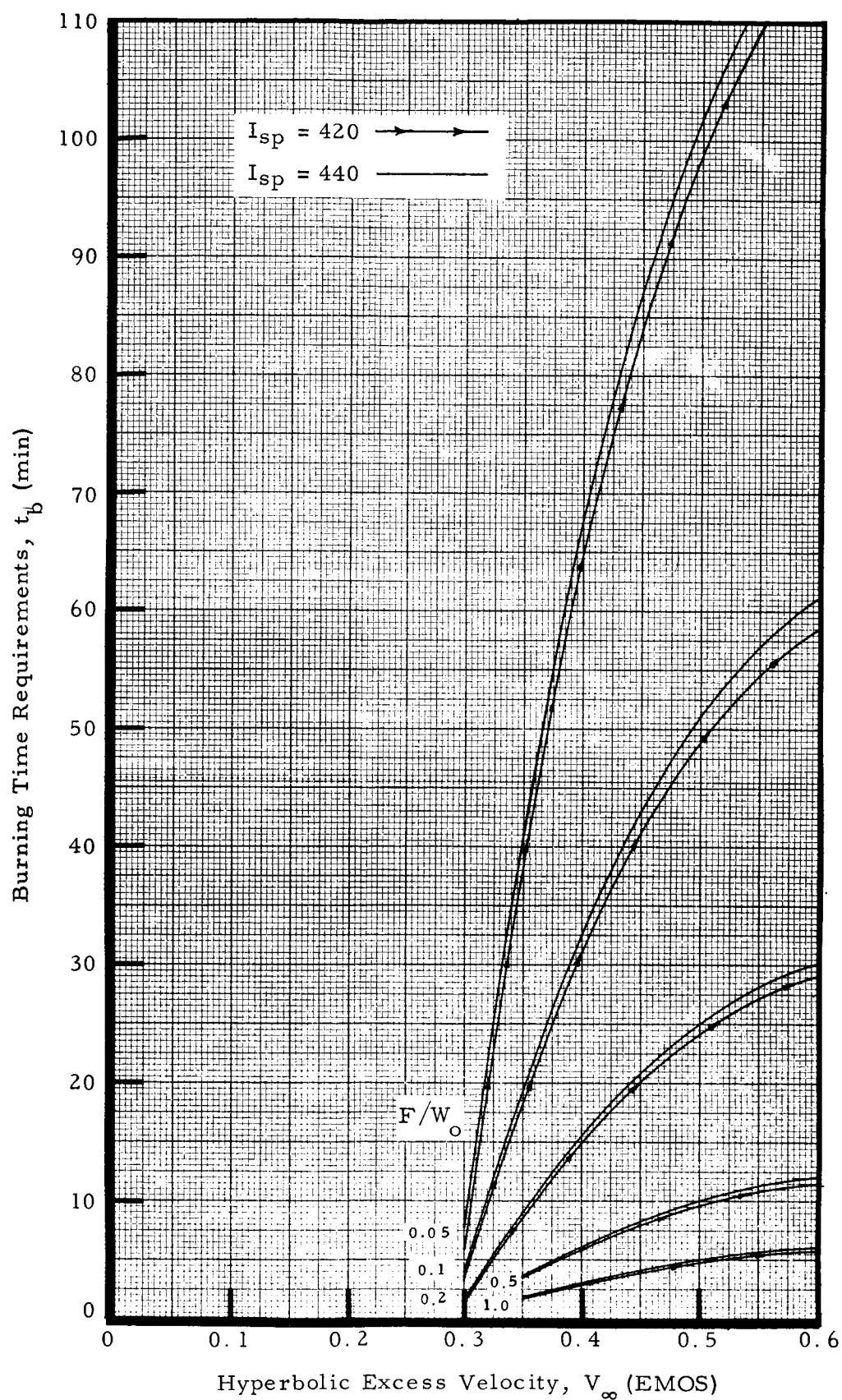


FIGURE 24c. BURNING TIME REQUIREMENTS FOR  
 $I_{sp} = 420$  s AND 440 s,  $(V_e)_{max} = 14000$  m/s



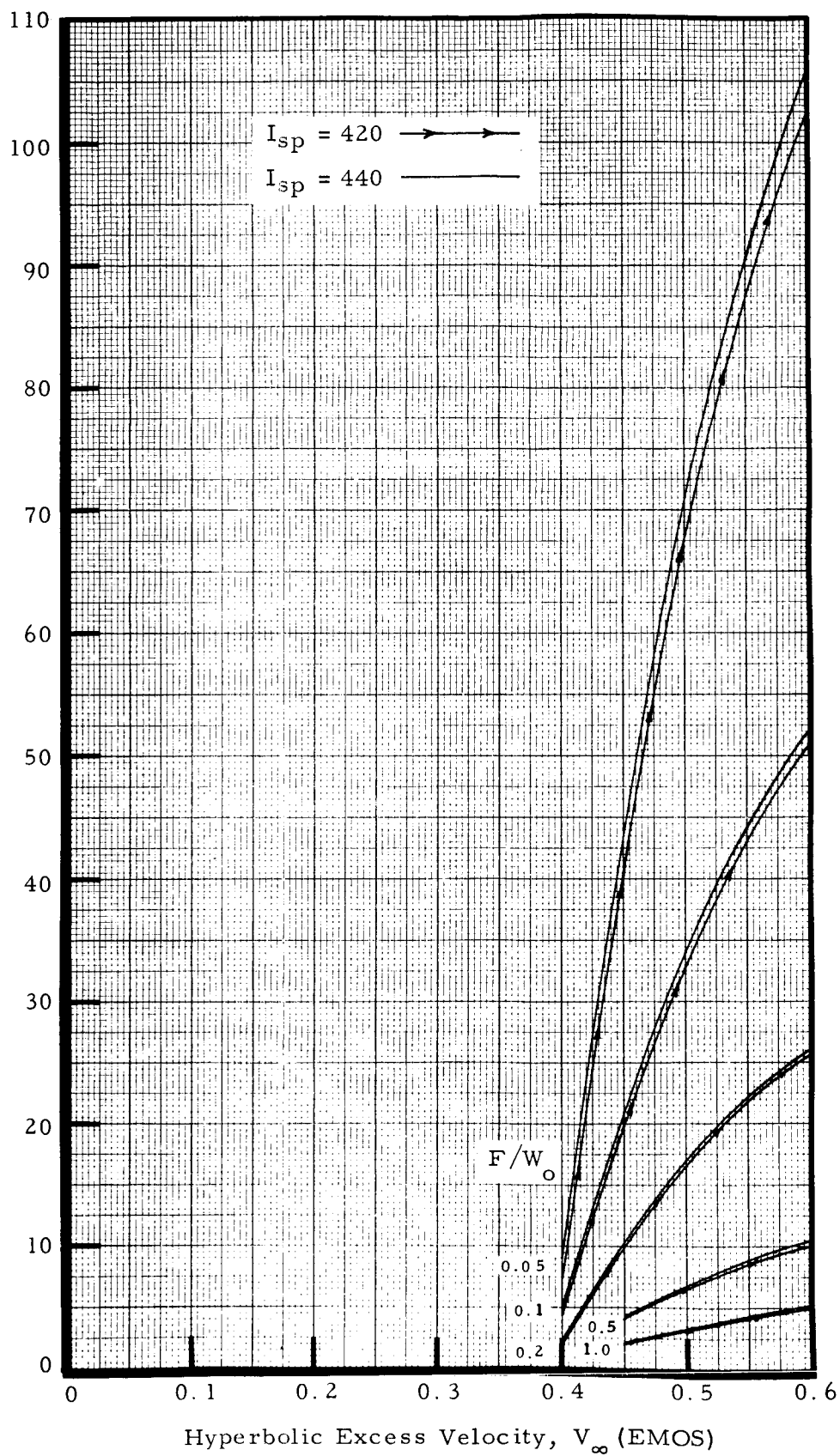


FIGURE 24d. BURNING TIME REQUIREMENTS FOR  
 $I_{sp} = 420$  s AND  $440$  s,  $(V_e)_{max} = 16000$  m/s



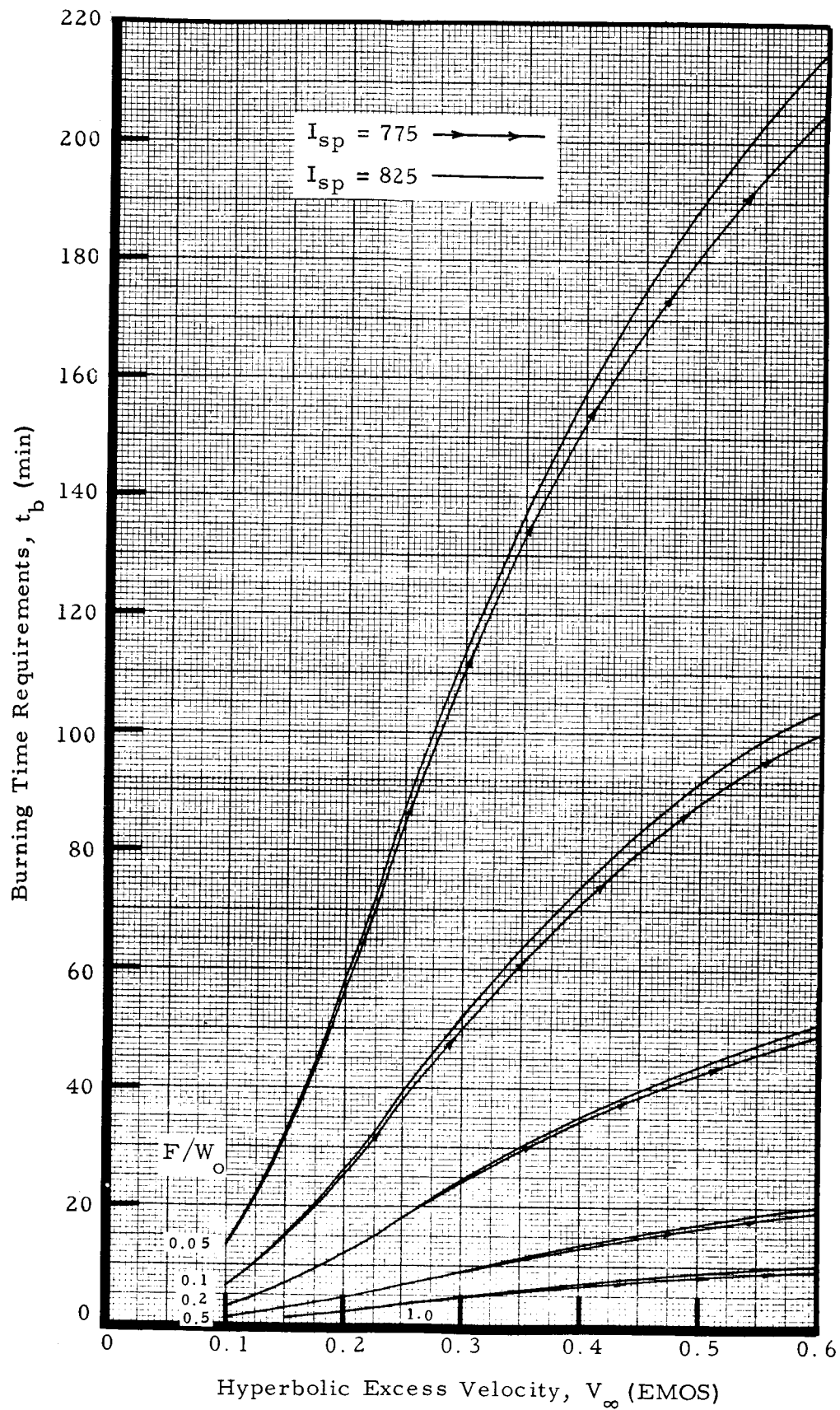


FIGURE 25a. BURNING TIME REQUIREMENTS FOR  
 $I_{sp} = 775$  s AND  $825$  s,  $(V_e)_{max} = 11030$  m/s

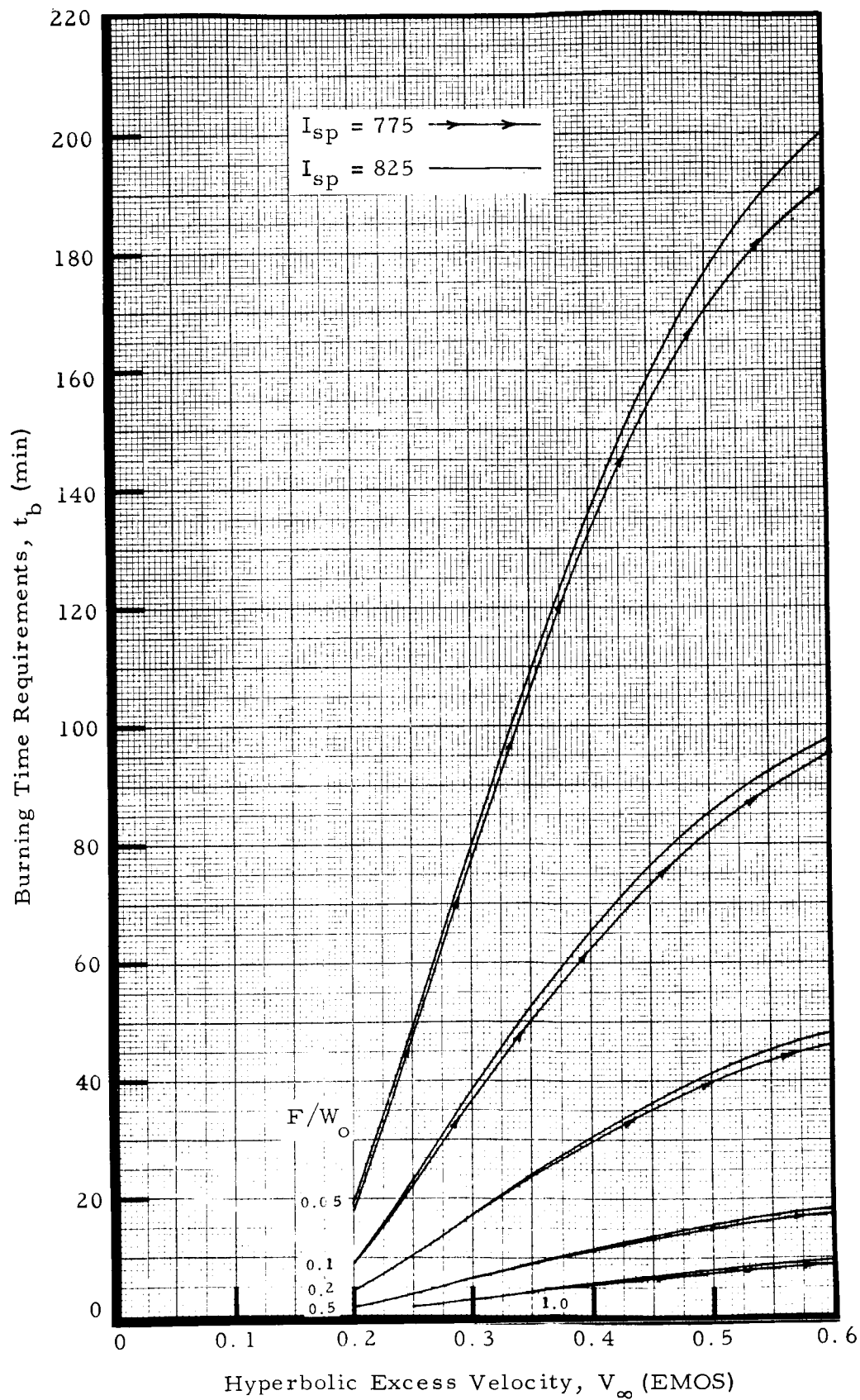


FIGURE 25b. BURNING TIME REQUIREMENTS FOR  
 $I_{sp} = 775$  s AND 825 s,  $(V_e)_{max} = 12000$  m/s

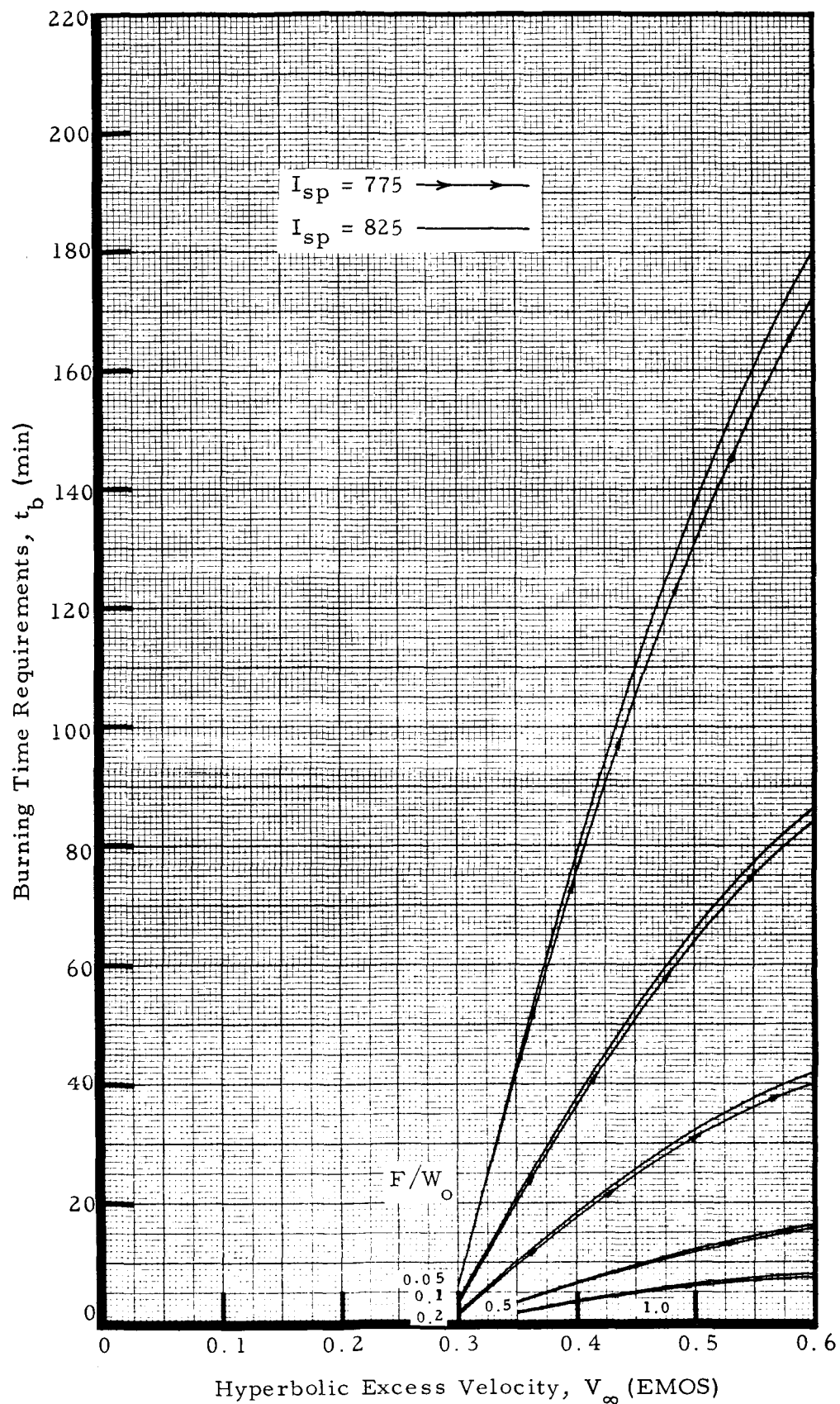


FIGURE 25c. BURNING TIME REQUIREMENTS FOR  
 $I_{sp} = 775$  s AND  $825$  s,  $(V_e)_{max} = 14000$  m/s

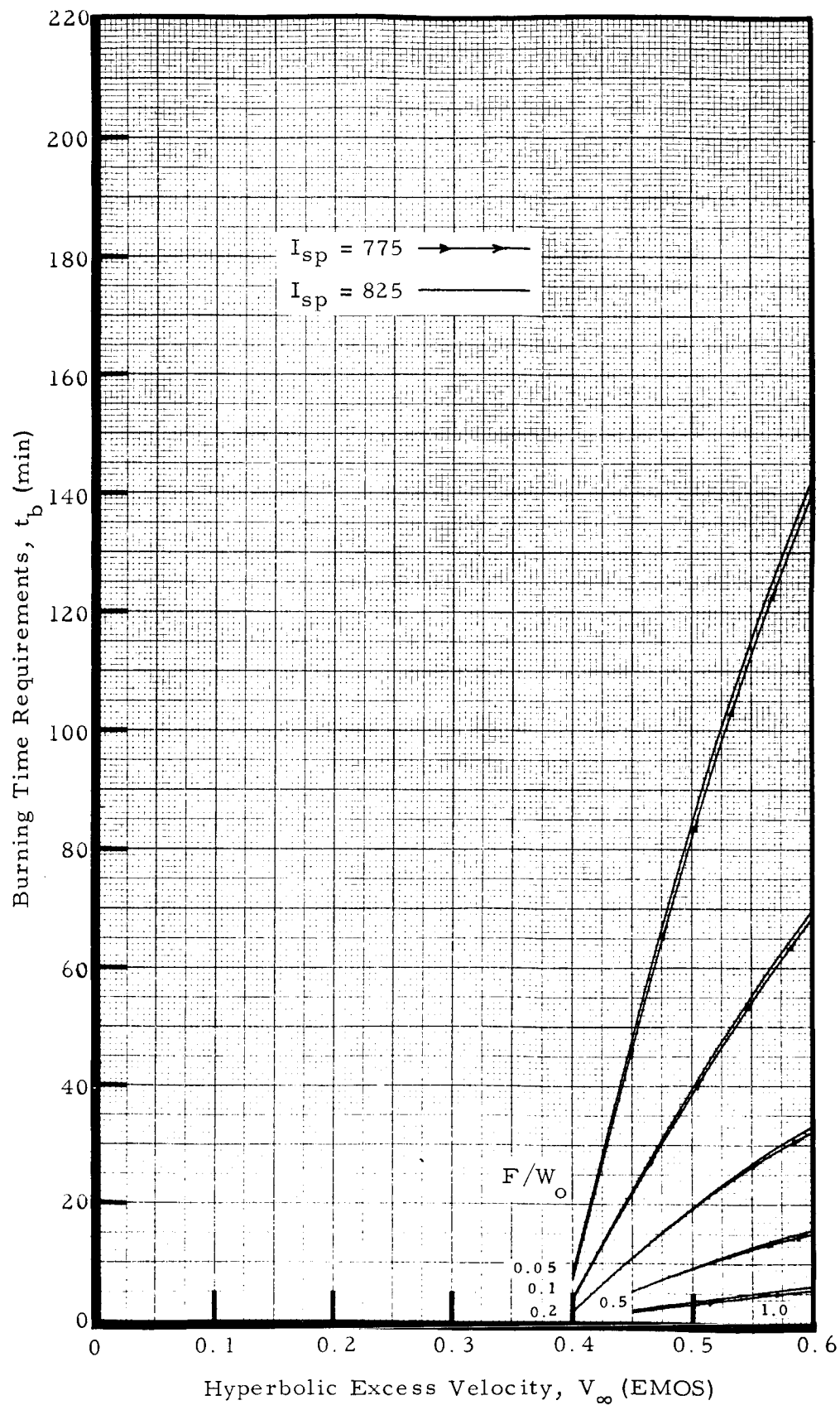


FIGURE 25d. BURNING TIME REQUIREMENTS FOR  
 $I_{sp} = 775$  s AND 825 s,  $(V_e)_{max} = 16000$  m/s

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APPROVAL

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VELOCITY REQUIREMENTS FOR THE EARTH RETURN PHASE  
OF PLANETARY MISSIONS

By

Robert M. Jones and William T. Stephens

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This document has also been reviewed and approved for technical accuracy.



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